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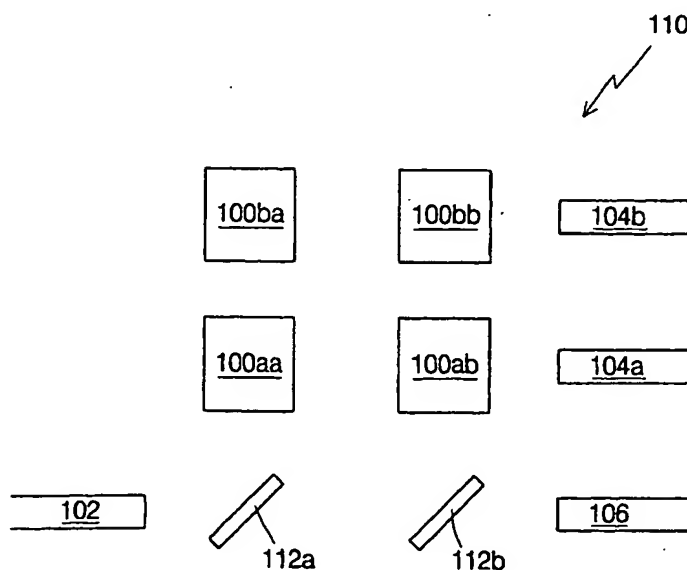
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- (71) Applicant (for all designated States except US): TRELIS PHOTONICS LTD. [IL/IL]; Rabin Bldg., Teradyon, 20179 Misgav (IL).
- (72) Inventors; and
- (75) Inventors/Applicants (for US only): AGRANAT, Aharon, J. [IL/IL]; Haarazim Street 29, 90805 Mevasseret Zion (IL). LITTWITZ, Elon [IL/IL]; Yuvalim 123, 20142 Misgav (IL). RAZVAG, Meir [IL/IL]; Haslav St. 422,
- (54) Agent: FRIEDMAN, Mark, M.; Beit Samueloff, Haomanim St. 7, 67897 Tel Aviv (IL).
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(54) Title: ELECTROHOLOGRAPHIC WAVELENGTH SELECTIVE PHOTONIC SWITCH FOR WDM ROUTING



(57) Abstract: A device (110) for switching light of one or more discrete wavelengths to one or more output conduits (106). The device (110) includes fibers (a-b) for each wavelength and for each output conduit (106), an electroholographic switch (100aa-ab) for switching a controllable portion of the light of each wavelength to each output conduit (106), the electroholographic switches (100aa-bb) of a common output conduit (106) being optically coupled, the electroholographic switches (100aa-bb) of a common wavelength being optically coupled.

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## ELECTROHOLOGRAPHIC WAVELENGTH SELECTIVE PHOTONIC SWITCH FOR WDM ROUTING

### FIELD AND BACKGROUND OF THE INVENTION

5       The present invention relates to switch arrays useful in optical communications based on wavelength division multiplexing (WDM) and, more particularly, to a wavelength selective cross-connect and methods for its use.

10       An optical fiber communication channel is a light beam, propagating in a medium such as an optical fiber, whose intensity is modulated in time according to the data to be carried on the channel. In WDM, each of  $N$  channels is carried on the same optical fiber at a different carrier wavelength. In the current state of the art, such a WDM link can have up to 80 channels, at 80 discrete wavelengths separated by a wavelength difference  $\Delta\lambda$  which may correspond to a frequency separation as small as 100 GHz.

15       Fast multidimensional switches are essential building blocks in high speed data communication systems, multimedia services, or high performance parallel computers. However, electronic implementations of such switches are close to their inherent limits. It is evident that it will not be possible to meet the demands of the emerging broadband communication applications by the existing electronic switching  
20       technology. Furthermore, electronic switching devices are not capable of direct integration with the optical fiber communication systems, which are becoming the dominant communications technology. Optical implementation of switching devices possesses several inherent advantages over their electronic counterparts.

25       Holographic optical elements and volume holograms have been used recently for two dimensional steering of light beams in optical interconnect networks, especially for highly parallel computer interconnects. However, such systems have generally relied, at least in the case of volume holograms, either on the use of a number of fixed holograms, the desired one of which is reconstructed using a reference beam selected by means of its wavelength or direction of incidence, or on  
30       the rewriting of the desired hologram in real time immediately before each steering action to be performed. Therefore, such holograms are not directly electrically

switchable, and thereby do not provide for simple system construction and high speed operation.

With the increase of the bit throughput rate in optical fiber communication systems by using WDM, cost effective light sources with very narrow spectral  
5 linewidths have been developed. The development of such lasers for optical communications has enabled the use of volume (thick) holograms as routing devices. Because such holograms are inherently extremely wavelength sensitive, their use had not previously been feasible commercially. The use of thick holograms now enables the routing of different WDM communication channels to different destinations in the  
10 same network, and thus allows three dimensional steering. However, to date, optical switches based on the use of prior art holograms, which are not directly electrically switchable, have not shown sufficient speed, nor do they possess sufficiently low cross-talk levels, to enable their use in the optical communication systems currently in use or under development.

15 Electroholography is a generic beam switching method based on controlling the diffraction from volume gratings by means of applying an electric field to the medium containing the grating. Electroholography can be implemented by the voltage controlled photorefractive effect realized in paraelectric photorefractive crystals wherein the electro-optic effect is quadratic. Here the grating is initially stored in the  
20 medium in the form of a photorefractive space charge, that induces an induced polarization grating and is consequently transformed by the quadratic electro-optic effect into an index of refraction (birefringence) grating when an electric field is applied to the medium. Alternatively, Electroholography can be implemented by the dielectric photorefractive effect where the grating is initially stored in the form of a  
25 grating of the dielectric constant, and is transformed by the quadratic electro-optic effect into an index of refraction (birefringence) grating when an electric field is applied to the medium. In the latter case the dielectric grating can be created by the creation of a spatial variation of the chemical composition in the crystal that induces a spatial variation of the phase transition temperature.

30 Aharon Agranat et al., in PCT/IL99/00368, which is incorporated by reference for all purposes as if fully set forth herein, teaches an electroholographic switch that is

particularly useful in optical communications. Electroholography enables the reconstruction process of volume holograms to be controlled by means of an externally applied electric field. Electroholography is based on the use of the voltage controlled photorefractive effect in the paraelectric phase, where the electro-optic effect is quadratic. Volume holograms stored as a spatial distribution of space charge in a paraelectric crystal can be reconstructed by the application of an electric field to the crystal. This field activates prestored holograms which determine the routing of data-carrying light beams.

The implementation of electroholography-based devices requires the use of a paraelectric photorefractive crystal with suitable properties, such as potassium tantalate niobate (KTN), strontium barium niobate (SBN), or especially potassium lithium tantalate niobate (KLTN), as taught by Hofmeister et al. in US Patents Nos. 5,614,129 and 5,785,898, which are incorporated by reference for all purposes as if fully set forth herein. KLTN doped with copper and vanadium is particularly suitable for use as the medium for electroholographic devices.

Unlike conventional holographic memory components based on conventional photorefractive crystals, which can be written and read only in the visible, electroholographic devices based on KLTN and similar materials can be operated in the near infra-red regions of the spectrum, including at 1.3  $\mu\text{m}$  and 1.55  $\mu\text{m}$ , wavelengths which are now commonly used in standard communication systems.

Figures 1A and 1B illustrate schematically the two states of an electroholographic 1x2 switch 100 of Agranat et al. that is based on a single paraelectric photorefractive crystal 10 that incorporates a prestored electroholographic (EH) grating. A pair of electrodes 12, 14 is deposited on two opposite faces of crystal 10. Paraelectric photorefractive crystals 10 could be of a material such as KTN, SBN, or especially KLTN. When a voltage  $V$ , is applied across electrodes 12, 14, a spatial modulation of the refractive index of crystal 10 is produced from the spatially modulated space charge field, set up according to the information carried by the volume hologram previously written into crystal 10. Thus, a diffraction grating 17 is effectively established in crystal 10 by the application of the voltage difference  $V$  to electrode pair 12-14.

Figure 1A shows one state of this switch 100 activated by applying a voltage  $V_0$  (i.e.  $V=V_0$ ) to crystal 10. In this state, an optical signal inputted along a path 16 passes to an output port 18. In this case, the residual power which remains in the input beam passes to an output port 20. Figure 1B shows the second state of this switch 100. Here a zero voltage (i.e.  $V=0$ ) is applied to crystal 10. Here the optical signal inputted along a path 16 passes to an output port 20. In both states, optical signals carried on channels whose carrier wavelengths  $\lambda$  are not affected by grating 17 (as determined by the Bragg condition) pass unswitched to port 20. A photodetector 21 may be placed in the optical path defined by port 20, in which case the residual power remaining after input beam 16 traverses this switch 100 is used for management and monitoring purposes, as described in detail in IL 125241.

Figures 1C and 1D illustrate schematically the two states of an electroholographic 1x2 switch 100 of Agranat et al. that is based on two paraelectric photorefractive crystals 10 and 11. Each crystal 10 or 11 incorporates a prestored electroholographic (EH) grating, with electrode pair 12, 14 deposited on two opposite faces of crystal 10 and electrode pair 13, 15 deposited on two opposite faces of crystal 11. Paraelectric photorefractive crystals 10 and 11 could be of a material such as KTN, SBN, or especially KLTN. When a voltage  $V_0$  is applied to either of the two pairs of electrodes 12, 14 and 13, 15, a spatial modulation of the refractive index of the respective crystal is produced from the spatially modulated space charge field, set up according to the information carried by the volume hologram previously written into crystal 10 or 11. Thus, a diffraction grating (17 in crystal 10, or 19 in crystal 11) is effectively established in crystal 10 or 11 by the application of the voltage to the electrode of the respective crystal.

Figure 1C shows one state of this switch 100 activated by applying a voltage  $V_0$  (i.e.  $V_1=V_0$ ) to crystal 10 and zero voltage (i.e.  $V_2=0$ ) to crystal 11. In this state, an optical signal inputted along a path 16 passes to an output port 18. Figure 1D shows the second state of this switch 100. Here a zero voltage (i.e.  $V_1=0$ ) is applied to crystal 10 and voltage  $V_0$  (i.e.  $V_2=V_0$ ) is applied to crystal 11. Here the optical signal inputted along a path 16 passes to an output port 20. In both cases, the residual power which remains in the input beam is blocked by a block 21. Block 21 may be replaced

by a photodetector, in which case the residual power remaining after input beam 16 traverses this switch 100 is used for management and monitoring purposes, as described in detail in IL 125241.

If  $V_1$  and  $V_2$  both are set equal to  $V_0$ , then part of the optical signal is diffracted to output port 18, and the residual, that is not diffracted to output port 18, is diffracted to output port 20. If diffraction gratings 17 and 19 are set up with different grating spacings, to diffract light of different wavelengths, then switch 100 of Figures 1C and 1D functions as two switches 100 of Figures 1A and 1B configured in series.

The mechanism by which the electroholographic switch operates is based on the use of the voltage controlled photorefractive effect, as described by A. J. Agranat, V. Leyva and A. Yariv in "Voltage-controlled photorefractive effect in paraelectric  $\text{KTa}_{1-x}\text{Nb}_x\text{O}_3\text{CuV}$ ", *Optics Letters*, vol. 14 pp. 1017-1019 (1989). The photorefractive effect enables the recording of optical information in a crystal, by spatially modulating its index of refraction in response to light energy it absorbs. The absorbed light photoionizes charge carriers from their traps to the conduction band (electrons) or the valence band (holes). The photoionized charge carriers are transported and eventually retrapped, forming a space charge field spatially correlated with the exciting illumination, and inducing a modulation in the index of refraction through the electrooptic effect. This mechanism is the basis for information storage in the form of phase holograms that can be selectively retrieved by applying the reconstructing (reading) light beam at the appropriate wavelength and angle.

Recently, it has been shown that it is also possible to introduce dipolar holographic gratings into photorefractive crystals by the introduction of a spatial modulation of the low frequency dielectric constant. This effect has been described by A. J. Agranat, M. Razvag and M. Balberg in "Dipolar holographic gratings induced by the photorefractive process in potassium lithium tantalate niobate at the paraelectric phase", *Journal of the Optical Society of America B*, vol. 14 pp. 2043-2048 (1997).

In the paraelectric phase, the efficiency of these effects can be controlled by applying an external electric field on the crystals during the reading (reconstructing) stage. Electroholography is based on this capability.

As indicated above, the physical basis of electroholography is the voltage controlled photorefractive (PR) effect. In general, the PR effect enables the recording of optical information in a crystal, by spatially modulating the index of refraction of the crystal in response to light energy that the crystal absorbs. In its simplest form the photorefractive effect is initiated by illuminating a crystal with the interference pattern of two mutually coherent beams. The absorbed light photoionizes charge carriers from their traps to the conduction band (electrons) or the valence band (holes). The photoionized charge carriers are transported and eventually retrapped, forming a space charge field that is spatially correlated with the exciting illumination, and inducing a modulation in the index of refraction of the crystal through the electrooptic effect.

In most PR crystals the electrooptic effect is linear. However, in PR crystals at the *paraelectric* phase the electrooptic effect is quadratic. Consequently, the induced changes in the index of refraction are given by:

$$\Delta n = \frac{1}{2} n_0^3 g_{eff} P^2 \quad (1)$$

where  $\Delta n$  is the induced change in the index of refraction,  $n_0$  is the refractive index,  $g_{eff}$  is the effective quadratic electrooptic coefficient, and  $P$  is the low frequency electric polarization. When a space charge field  $E_{sc}(\vec{r})$  is formed in the crystal, the polarization becomes:

$$P = \epsilon [E_0 + E_{sc}(\vec{r})] \quad (2)$$

where  $\epsilon$  is the dielectric constant (which close to the phase transition obeys  $\epsilon/\epsilon_0 \gg 1$ , where  $\epsilon_0$  is the permittivity of the vacuum,  $8.854 \times 10^{-12}$  F/m),  $E_0$  is the externally applied field, and it is assumed that the polarization is in the linear region, where  $P = \epsilon_0(\epsilon/\epsilon_0 - 1)E$ . Substituting equation (2) into equation (1) gives an expression for the spatial distribution of the space charge field, which includes 3 terms:

$$\Delta n(\vec{r}) = \frac{1}{2} n_0^3 g \epsilon^2 [E_0^2 + 2E_0 E_{sc}(\vec{r}) + E_{sc}^2(\vec{r})] \quad (3)$$

Consider the diffraction of a light beam with wavelength  $\lambda$ , which is incident on the crystal at an angle  $\theta$ , and fulfills the Bragg condition given by

$$\Lambda = \lambda / 2 n_0 \sin \theta \quad (4)$$

where  $\Lambda$  is the period of the grating formed by the PR process, and  $n_0$  is the crystal



refractive index. The first term in equation (3) is spatially uniform and thus does not contribute to the diffraction. In principle, this term should affect the diffraction efficiency by detuning the Bragg condition, as it affects the bulk index of refraction  $n_0$ . However, in symmetric transmission gratings, the detuning of the Bragg condition is canceled out by the change in the internal angle of incidence caused by the refraction of the beam as it enters the crystal (Snell's law). The third term in equation (3) induces a grating with a period of  $\Lambda/2$ . Therefore, this grating is not Bragg matched with the incident beam and does not contribute to the diffraction. Thus, the only term in equation (3) that contributes to the diffraction is the second term. The amplitude of the index grating that it induces is given by

$$\delta [\Delta n(\vec{r})] = n_{0,3} g_{eff} \epsilon^2 E_0 E_{\omega}(\vec{r}) \quad (5)$$

It can be seen that the space charge field spatial distribution is transformed into a modulation of the refractive index that diffracts light only in the presence of the externally applied electric field.

The diffraction efficiency of a plane wave diffracted by a sinusoidal phase transmission grating stored at the paraelectric phase is given by (H. Koglenik, "Coupled wave theory for thick hologram gratings", *Bell Syst. Tech. J.* vol. 48 pp. 2909-2949, 1969):

$$\eta = \exp(-\alpha d) \sin^2 \left( \frac{\pi d}{\lambda \cos \theta} n_{0,3} g_{eff} E_0 E_{\omega} \right) \quad (6)$$

where  $d$  is the thickness of the crystal and it is assumed that the Bragg condition is satisfied. Note that this definition of the diffraction efficiency does not include scattering by defects of the crystal and reflection from the crystal facets. It can be seen from equation (6) that the applied external field  $E_0$  controls the diffraction efficiency of the grating induced by the space charge.

Therefore, the use of the quadratic electrooptic effect enables an analog control of the reconstruction of the information. This is the voltage controlled PR effect discussed above.

As explained above, except for the case of symmetrical transmission holograms, due to the first term in equation (3), the application of an electric field on a crystal containing holograms in the form of distributed space charge, also causes a

detuning of the Bragg condition. This phenomenon has been described in detail by M. Balberg, M. Razvag, E. Refaelli and A. J. Agranat in "Electric field multiplexing of volume holograms in paraelectric crystals" *Applied Optics*, vol. 37, pp. 841 - 847 (1998).

5 KLTN is a photorefractive crystal designed to be operated in the paraelectric phase, where the photorefractive effect is voltage controlled. The composition and method of production of this crystal are described in US 5,614,129 and in US 5,785,898. The preferred chemical composition of the KLTN crystal used in switch 100 is  $K_{0.9945}Li_{0.0055}Ta_{0.65}Nb_{0.35}O_3$ . The phase transition temperature of the KLTN crystal used, as determined by measurement of the temperature dependence of the dielectric constant, is  $T_c=26^\circ C$ . In order to improve the performance of the crystal, prior to writing the holograms, the crystals are subjected to a poling process in which they are gradually cooled at  $0.5^\circ C/\text{minute}$  from  $40^\circ C$  to  $10^\circ C$  under an external field of  $2.1\text{kV/cm}$ , and then warmed-up to the operational temperature at the same rate. 15 During operation, the crystal is held at  $32^\circ C$ , which is  $6^\circ C$  above its phase transition temperature, well within the paraelectric phase. The temperature is maintained by means of a stabilized thermoelectric element (not shown) in juxtaposition to crystals 10 and 11.

## 20 SUMMARY OF THE INVENTION

According to the present invention there is provided a device for switching light of any of a plurality of discrete wavelengths to any of a plurality of output conduits, including: (a) for each wavelength and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength being optically coupled. 25

According to the present invention there is provided a method for switching light of any of a plurality of discrete wavelengths to any of a plurality of output conduits, including the steps of: (a) providing, for each wavelength and for each output conduit, a respective electroholographic switch; (b) for each wavelength. 30

diverting the light of the each wavelength to the electroholographic switches of the each wavelength; and (c) for each electroholographic switch, setting a state of the each switch so as to further divert a desired portion of the light of the respective wavelength of the each switch to the respective output conduit of the each switch.

- 5           According to the present invention there is provided a device for switching light of any of a plurality of discrete wavelengths to any of a first and second pluralities of output conduits, including: (a) a first module including: (i) for each wavelength and for each output conduit of the first plurality, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the
- 10 each output conduit of the first plurality, the electroholographic switches of a common output conduit of the first plurality being optically coupled, the electroholographic switches of a common wavelength being optically coupled; and (b) a second module including: (i) for each wavelength and for each output conduit of the second plurality, an electroholographic switch for switching a controllable portion of the light of the
- 15 each wavelength to the each output conduit of the second plurality, the electroholographic switches of a common output conduit of the second plurality being optically coupled, the electroholographic switches of a common wavelength being optically coupled.

- According to the present invention there is provided a device for switching
- 20 light of any of a first and second pluralities of discrete wavelengths to any of a first and second pluralities of output conduits, including: (a) an uplink conduit; (b) a first module including: (i) for each wavelength of the first plurality of wavelengths and for each output conduit of the first plurality of output conduits, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the
- 25 each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength being optically coupled, and (ii) for each wavelength of the first plurality, a mechanism for diverting, to the uplink conduit, the light of the each wavelength remaining after the controllable portion of the light of the each wavelength is switched
- 30 to the first plurality of output conduits; and (c) a second module including: (i) for each wavelength of the second plurality of wavelengths and for each output conduit of the

second plurality of output conduits, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength being optically coupled, and (ii)  
5 for each wavelength of the second plurality, a mechanism, optically coupled to the uplink conduit, for diverting the light of the each wavelength to the respective electroholographic switches while passing the light of all other wavelengths.

According to the present invention there is provided a device for switching light of any of a first and second pluralities of discrete wavelengths to any of a  
10 plurality of output conduits, including: (a) a first module including: (i) for each wavelength of the first plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength of the first plurality to the each output conduit, the electroholographic switches of a common  
15 output conduit being optically coupled, the electroholographic switches of a common wavelength of the first plurality being optically coupled; and (b) a second module including: (i) for each wavelength of the second plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the  
20 each wavelength of the second plurality to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength of the second plurality being optically coupled.

According to the present invention there is provided a device for switching light of any of a plurality of discrete wavelengths from at least one of a plurality of input conduits to any one of a plurality of output conduits, including: (a) for each  
25 input conduit, a module including: (i) for each wavelength and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength being optically coupled, and (ii) for each wavelength, a  
30 mechanism for diverting the light of the each wavelength from the each input conduit to the respective holographic switches while passing the light of all other

wavelengths; and (b) for each output conduit, a multiplexer for combining outputs of all the respective electroholographic switches into the each output conduit.

According to the present invention there is provided a device for converting light of any of a first plurality of discrete wavelengths to light of any of a second plurality of discrete wavelengths, the first and second pluralities being equal in number, and then switching the light of the second plurality of discrete wavelengths to any of a plurality of output conduits, including: (a) a first module including: (i) a plurality of transponders, equal in number to the first plurality of wavelengths, each transponder outputting light of a respective wavelength of the second plurality, and (ii) for each wavelength of the first plurality and for each transponder, an electroholographic switch for switching a controllable portion of the light of the each wavelength of the first plurality to the each transponder, the electroholographic switches of a common transponder being optically coupled, the electroholographic switches of a common wavelength of the first plurality being optically coupled; and (b) a second module including: (i) for each wavelength of the second plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength of the second plurality to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength of the second plurality being optically coupled.

According to the present invention there is provided, in an optical communication system wherein signals are carried in a plurality of channels, each channel including light of a respective discrete wavelength, an add-drop multiplexer, for replacing at least one input signal with a corresponding at least one output signal on a respective subplurality of the channels, including: (a) an uplink conduit; (b) a drop module including: (i) a plurality of diversion conduits, (ii) for each wavelength of the subplurality and for each diversion conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength of the subplurality to the each diversion conduit, the electroholographic switches of a common diversion conduit being optically coupled, the electroholographic switches of a common wavelength of the subplurality being optically coupled, and (iii) a mechanism for

diverting the light of the each wavelength of the subplurality to the respective electroholographic switches while passing the light of all other wavelengths to the uplink conduit; and (c) an add module including: (i) a plurality of substitution conduits, and (ii) a mechanism for diverting light of the wavelengths of the subplurality from each substitution conduit to the uplink conduit.

According to the present invention there is provided, in an optical communications system wherein signals are carried in a plurality of channels via a common conduit, each channel having a respective discrete wavelength, a device for tapping the channels, including: (a) for each channel, a respective electroholographic switch for diverting a controllable portion of the signals of the each channel from the common conduit.

According to the present invention there is provided an electroholographic switch, for switching light of a certain wavelength, including: (a) a crystal of a photorefractive material including a plurality of electroholographic gratings, the electroholographic gratings being spaced apart laterally within the crystal; and (b) for each electroholographic grating, two electrodes for activating the each grating.

According to the present invention there is provided an optical switch including a paraelectric photorefractive material, wherein is stored a plurality of superposed holograms whose reconstruction is controllable by means of an applied electric field.

According to the present invention there is provided a method for determining a level of amplification of an optical signal for switching the optical signal to a primary output conduit, the method including the steps of: (a) providing at least one electroholographic switch for switching the optical signal to the primary output conduit; (b) diverting a first portion of the optical signal through the electroholographic switch to the primary output conduit and a second portion of the optical signal through the electroholographic switch to a secondary output conduit; (c) detecting a power of the second portion; and (d) based on the detected power of the second portion, adjusting a power of the first portion.

According to the present invention there is provided a method for analyzing at least one quality characteristic of an optical signal, the method including the steps of:

(a) providing an electroholographic switch for diverting at least a portion of the optical signal for analysis; (b) diverting the at least a portion of the optical signal for analysis; and (c) analyzing the at least a portion of the optical signal to determine the at least one-quality characteristic.

5        According to the present invention there is provided a method of communication wherein optical signals are transmitted through an optical communication network, the optical signals being encoded in a plurality of channels propagating in an optical medium, the method including the steps of: (a) diverting  
10        only a portion of the optical signals in each channel while a remainder of the optical signals in each channel continues to propagate in the optical medium; (b) converting each portion to an electronic signal; and (c) managing the network in accordance with the electronic signal.

      The basic device of the present invention receives, from an input conduit, a plurality of concurrent WDM data streams (channels)  $i$ , each carrying data at a  
15        different carrier wavelength  $\lambda_i$ , diverts one or more of the data streams to any desired degree, from no diversion to almost full diversion, to one or more output conduits, and passes the undiverted remainder of the data streams to a common output conduit. Most typically, the input and output conduits are optical fibers.

      Figure 2 shows, schematically, a basic embodiment of the basic device of the  
20        present invention. Device 110 receives a plurality of concurrent WDM data streams from an input optical fiber 102. The two data streams whose carrier wavelengths are  $\lambda_1$  and  $\lambda_2$  are partially or totally diverted to output optical fibers 104a and 104b. The remainder of the input data streams continues undiverted into common output optical fiber 106.

25        Device 110 includes two wavelength-specific filters 112a and 112b and four switches of the type illustrated in Figure 1, switch 100aa, switch 100ab, switch 100ba and switch 100bb, arranged in a matrix as shown. Filter 112a diverts the data stream whose carrier wavelength is  $\lambda_1$  to switches 100aa and 100ba. Filter 112b diverts the data stream whose carrier wavelength is  $\lambda_2$  to switches 100ab and 100bb. Filters 112  
30        are demultiplexing narrow-band filters, for example, interference filters or Bragg grating filters. Such filters are well-known in the art, and are used, for example, in the

DWDM1F series of demultiplexers available from E-TEK dynamics, Inc. Of San Jose CF, USA. Alternatively, filters 112 are photorefractive crystals, such as crystals 10 and 11, with diffraction gratings such as gratings 17 and 19 incorporated therein and activated by appropriate voltages to provide nearly full diversion of their respective data streams.

Switches 100 are illustrated as being positioned in a square grid. In general, the grid is oblique, with the grid angles and the grating spacings of the holographic gratings of switches 100 chosen, in accordance with the Bragg condition, so that switches 100aa and 100ba act only on light in a narrow band of wavelengths (narrower than  $\Delta\lambda$ ) around carrier wavelength  $\lambda_1$  and pass light of all other wavelengths, and so that switches 100ab and 100bb act only on light in a narrow band of wavelengths around carrier wavelength  $\lambda_2$  and pass light of all other wavelengths. In the preferred embodiment of device 110, the grid is in fact square (or, more generally, rectangular; the grid angle is  $90^\circ$ ), in order to obtain as compact a device 110 as possible and to simplify the production of device 110 with regard to issues such as alignment and collimation. The grating spacings of the holographic gratings are chosen to obtain Bragg angles of  $45^\circ$  relative to the corresponding wavelengths.

By appropriately adjusting the voltages applied to switches 100aa and 100ba, the data stream of carrier wavelength  $\lambda_1$  is diverted to any desired degree, from no diversion to almost total diversion, to either or both of output optical fibers 104. Similarly, by appropriately adjusting the voltages applied to switches 100ab and 100bb, the data stream of carrier wavelength  $\lambda_2$  is diverted to any desired degree, from no diversion to almost total diversion, to either or both of optical fibers 104. The diversion of the data stream of carrier wavelength  $\lambda_1$  is totally independent of the diversion of the data stream of carrier wavelength  $\lambda_2$ . Either output optical fiber 104 may receive only the data stream of carrier wavelength  $\lambda_1$ , only the data stream of carrier wavelength  $\lambda_2$ , both data streams or neither data stream. Switches 100ab and 100bb have no effect on the data stream of wavelength  $\lambda_1$ , so that the data stream of wavelength  $\lambda_1$  passes unaffected through switches 100ab and 100bb. Thus, each row of switches 100 in device 110 functions as an optical coupler.

In the most preferred embodiment of device 110, all four switches 100 are



fabricated in the same photorefractive crystal. Such an array or matrix of electroholographic switches constitutes an invention in its own right.

In one enhanced embodiment of device 110, the columns of switches 100 end in detectors that receive light of wavelengths  $\lambda_1$  and  $\lambda_2$  not diverted by switches 100.

5. These detectors convert the undiverted light to electrical voltages that are proportional to the intensities of the undiverted light. These detectors typically are integrated in electronic devices that perform system functions such as error detection, network monitoring and analysis, and data monitoring and analysis.

In a second enhanced embodiment of device 110, the columns of switches 100  
10 end in additional electroholographic switches for diverting the light of wavelengths  $\lambda_1$  and  $\lambda_2$  not diverted by switches 100 to a common uplink conduit.

Third and fourth enhanced embodiments of device 110 includes mechanisms for verifying that switches 100 actually switch the data streams as intended. In the third enhanced embodiment, a diversion mechanism such as a beamsplitter or yet  
15 another electroholographic switch intervenes between each row of switches 100 and the corresponding output optical fiber 104. The diversion mechanism diverts a preferably controllable portion of the light emerging from that row of switches 100 to a detector. In the fourth enhanced embodiment of device 110, each column of switches 100 is provided with a light source that emits coherent light at a wavelength  
20 other than the wavelength switched by that column of switches 100. This light also is diverted, at least partially, by the holographic gratings of switches 100 of that column, but in a direction other than the row direction, to be detected by appropriate detectors.

Compound devices of the present invention are based on basic devices of the present invention used as modules.

25 In a first compound device of the present invention, based on two modules, the second module lacks filters 112, and the light not switched by the columns of switches 100 of the first module goes directly to the columns of switches 100 of the second module, to be switched, entirely or in part, to output optical fibers 104 of the second module.

30 In a second compound device of the present invention, also based on two modules, the first module is the enhanced module, described above, in which the

columns of switches 100 end in additional electroholographic switches that divert the light emerging from the columns to a common uplink conduit. The uplink conduit then serves as input conduit 102 of the second module.

In a third compound device of the present invention, also based on two  
5 modules, both modules are the enhanced module, described above, in which the columns of switches 100 end in additional electroholographic switches that divert the light emerging from the columns to a common uplink conduit, and the uplink conduit is shared by both modules. In addition, the rows of switches 100 of the two modules are coupled into common output optical fibers 104, either by optically coupling the  
10 rows of switches 100 of the first module to the rows of switches 100 of the second module, or by joining output optical fibers 104 of the first module to output optical fibers 104 of the second module at y-junctions.

In a fourth compound device of the present invention, based on several modules, each with its own input optical fiber 102, corresponding output optical fibers  
15 104 of the various modules lead to common multiplexers. The inputs of each multiplexer then are combined into a common output fiber leading from that multiplexer.

In a fifth compound device of the present invention, based on two modules, the first module has an equal number of rows and columns of switches 100, and the  
20 output conduits of the first module are not optical fibers 104, but instead are transponders, each of which converts input light into similar light at a respective output wavelength. Each transponder is optically coupled to a respective column of switches 100 of the second module.

An add-drop multiplexer of the present invention, for removing data streams at  
25 carrier wavelengths  $\lambda_1$  and  $\lambda_2$ , from a collection of concurrent data streams that include data streams at these and other wavelengths, and substituting for them other data streams at carrier wavelengths  $\lambda_1$  and  $\lambda_2$ , includes a drop module and an add module. The drop module is a basic device of the present invention. Output optical fibers 104 of the drop module are diversion conduits that carry the data streams being  
30 dropped to their respective destinations. The add module receives the surviving data streams from the drop module, and also receives input from substitution conduits that

carry substitution data streams at their respective carrier wavelengths,  $\lambda_1$  or  $\lambda_2$ . The substitution data streams are merged with the input from the drop module using optical components such as y-junctions, or alternatively using electroholographic switches in a manner similar to that used in the second enhanced embodiment of device 110 to merge undiverted light of wavelengths  $\lambda_1$  and  $\lambda_2$  to a common uplink conduit.

A holographic tap of the present invention diverts portions of selected channels from a common optical fiber, using electroholographic switches 100 specific to the carrier wavelengths of the selected channels. The diverted light is converted to electronic signals by suitable detectors, and the signals are used for network management functions. For example, in a holographic tap downstream from an amplifier, the voltages applied to switches 100 are adjusted to equalize the powers in the tapped channels.

The wavelength specific photonic switching technology provides a way to "access" the optical transmissions without intervening the all-optical path, i.e. the data path. It is achieved by using the residual ("left-over") signal from the switching of the optical signals in ELECTROHOLOGRAPHIC switches. The residual signal is a well-defined portion of the original signal, so it can be used to restore the characteristics of the original wave for network management analysis. The residual wavelength can be diverted to an output conduit as optical signal and/or converted to electrical signals by detector for power, error, and data analysis. Thus, these signals can be analyzed by network management devices which are able to determine the efficacy of transmission according to the analysis of the residual wavelength.

As described in greater detail below, a number of different embodiments of optical switches are suitable for use with these network management devices, although of course other implementations of optical switches could also be used. The network management devices of the present invention can be used to ensure the quality of the optical signal transmission and to detect when such quality of transmission falls below a minimum level at any one optical switch.

It will be appreciated that the various features of the enhanced and compound embodiments of the device of the present invention may be used together in a single

enhanced/compound device of the present invention.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to  
5 the accompanying drawings, wherein:

FIG. 1 illustrates, schematically, the operation of the prior art electroholographic switches upon which the present invention is based;

FIG. 2 is a schematic illustration of the most basic embodiment of a basic device of the present invention;

10 FIG. 3 is a schematic illustration of an enhanced embodiment of the device of FIG. 2;

FIG. 4 is a schematic illustration of another enhanced embodiment of the device of FIG. 2;

15 FIG. 5 is a schematic illustration of a third enhanced embodiment of the device of FIG. 2;

FIG. 6 is a schematic illustration of a compound device of the present invention;

FIG. 7 is schematic illustration of another compound device of the present invention;

20 FIG. 8 is a schematic illustration of a third compound device of the present invention;

FIG. 9 is a schematic illustration of a fourth compound device of the present invention;

25 FIG. 10 is a schematic illustration of a fifth compound device of the present invention;

FIG. 11 is a schematic illustration of a sixth compound device of the present invention;

FIG. 12 is a schematic illustration of the use of an electroholographic tap of the present invention for power equalization;

30 FIG. 13 is a schematic illustration of an add-drop multiplexer of the present invention;

FIG. 14 is a schematic illustration of an alternative add module for the add-drop multiplexer of FIG. 13;

FIG. 15 illustrates an alternate method of power equalization in the add-drop multiplexer of FIG. 13;

5        FIGs. 16A and 16B are side and front views of two electroholographic switches fabricated on the same photorefractive crystal;

FIG. 17 is a schematic block diagram of a preferred detection module according to the present invention;

10        FIG. 18 is a schematic block diagram of a preferred optical signal power level determiner according to the present invention;

FIG. 19 is a first preferred embodiment of the management analyzer according to the present invention, dedicated to a single channel;

FIG. 20 is a second preferred embodiment of the management analyzer according to the present invention, capable of switching channels; and

15        FIG. 21 is a third preferred embodiment of the management analyzer according to the present invention, in a mixed configuration.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

20        The present invention is of a wavelength specific cross-connect which can be used to switch input optical data streams among a plurality of output channels. Specifically, the present invention can be used for cross-connecting channels, for grouping, for broadcasting and for multicasting.

25        The principles and operation of a wavelength specific cross-connect according to the present invention may be better understood with reference to the drawings and the accompanying description.

The basic devices of the present invention are depicted herein with only two rows and two columns of switches 100 only for illustrational simplicity. Typically, a basic device of the present invention includes 32 columns and 8 rows of switches 100.

30        Referring again to the drawings, Figure 3 is a schematic illustration of an enhanced embodiment 120 of the basic device of the present invention. Device 120 includes, in addition to the components of device 110, two detectors 114, such as

photodiodes, at the output ends of respective columns of switches 100, two beamsplitters 116 at the output ends of respective rows of switches 100, and detectors 118, similar to detectors 114, for receiving light diverted by beamsplitters 116 from reaching the respective output optical fibers 104.

5        Detector 114a detects the intensity of light diverted to switches 100aa and 100ba by filter 112a but not diverted by switches 100aa and 100ba to output optical fibers 104. Similarly, detector 114b detects the intensity of light diverted to switches 100ab and 100bb by filter 112b but not diverted by switches 100ab and 100bb to output optical fibers 104. Detectors 114 convert the light incident thereon to electrical  
10        voltages that are proportional to the intensities of that light. These detectors typically are integrated in electronic devices that perform system functions such as error detection, network monitoring and analysis, and data monitoring and analysis. Thus, these detectors enable the implementation of *noninterfering* network management. Unlike the prior art method of network management, in which optical channels are  
15        converted to electronic signals, network management functions are implemented by manipulating these electronic signals, and , finally, these electronic signals are converted back to optical signals, the network management method of the present invention is based on electronic manipulation of signals created from diverted  
20        portions of the optical channels, while the undiverted portions of the optical channels continue to propagate in the optical fibers of the network.

One such application of detectors 114 and the associated electronics is to power equalizing. The fraction of the light diverted by any of switches 100 is a known function of the voltage applied to the switch. Therefore, the powers of the channels switched into output optical fibers 104 can be computed from the intensity  
25        readings obtained by detectors 114. The voltages applied to switches 100 then can be adjusted in a feedback loop to equalize the powers of the channels of carrier wavelengths  $\lambda_1$  and  $\lambda_2$  in output optical fibers 104.

Beamsplitter 116a diverts to detector 118a a fraction of the light that emerges from switches 100aa and 100ab. Similarly, beamsplitter 116b diverts to detector  
30        118b a fraction of the light that emerges from switches 100ba and 100bb. The intensities measured by detectors 118 are used to verify that switches 100 are in fact

diverting the desired proportions of light received from filters 112 to output optical fibers 104, as functions of the voltages applied to switches 100. The electrical signals produced by detectors 114 and 118 also may be used in selftest mode, to verify that the voltages applied to switches 100 do indeed activate the desired (row,column) pairs.

Alternatively, wide-band electroholographic switches are used in place of beamsplitters 116. A wide-band electroholographic switch is an electroholographic switch similar to switch 100 but having a holographic grating that interacts with and diffracts a wider range of wavelengths, at each incidence angle, than the wavelength difference  $\Delta\lambda$  that separates the distinct carrier wavelengths. Wide-band electroholographic switches have the advantage over beamsplitters 116 of being tunable: the fraction of the light diverted to detectors 118 is adjustable by adjusting the voltages applied to the switches.

Figure 4 is a schematic illustration of an enhanced embodiment 130 of the basic device of the present invention. Device 130 includes, in addition to the components of device 110, two sources 122 of coherent light beams 126 and four detectors 124. Sources 122 may include, for example, suitable lasers and suitable collimation optics. Source 122a directs a collimated beam 126a of coherent light, at a wavelength outside the band  $\lambda_1 \pm \Delta\lambda/2$ , down the left-hand column of switches 100. Beam 126a is diffracted by the holographic gratings of switches 100aa and 100ba, and is thereby at least partially diverted by switches 100aa and 100ba to respective detectors 124aa and 124ba. Because the wavelength of beam 126a differs from  $\lambda_1$ , diffracted beams 128aa and 128ba emerge from switches 100aa and 100ba at a different angle, according to the Bragg condition, relative to incident beam 126a, than the angle at which switches 100aa and 100ba divert light received from filter 112a towards output optical fibers 104. To illustrate this difference, Figure 4 is drawn with the angle at which switches 100aa and 100ba divert light received from filter 112a being a right angle, and the angle between incident beam 126a and diffracted beams 128aa and 128ba being an oblique angle. Similarly, source 122b directs a collimated beam 126b of coherent light, at a wavelength outside the band  $\lambda_2 \pm \Delta\lambda/2$ , down the right-hand column of switches 100. Beam 126b is diffracted by the holographic

gratings of switches 100ab and 100bb, and is thereby at least partially diverted by switches 100ab and 100bb to respective detectors 124ab and 124bb. Because the wavelength of beam 126b differs from  $\lambda_2$ , diffracted beams 128ab and 128bb emerge from switches 100ab and 100bb at a different angle, relative to incident beam 126b, than the angle at which switches 100ab and 100bb divert light received from filter 112b towards output optical fibers 104. Furthermore, beams 126a and 126b, by virtue of having wavelengths different from  $\lambda_1$  and  $\lambda_2$ , respectively, pass through filters 112 without being diverted towards common output optical fiber 106. Therefore, none of the light from sources 122 enters output optical fibers 104 and 106 to contaminate the data streams propagating therein. As in the case of detectors 118 of Figure 3, the intensities measured by detectors 124 are used to verify that switches 100 are in fact diverting the desired proportions of light received from filters 112 to output optical fibers 104, as functions of the voltages applied to switches 100.

Figure 5 is a schematic illustration of an enhanced embodiment 140 of the basic device of the present invention. Device 140 includes, in addition to the components of device 110, two more electroholographic switches 100' at the output ends of respective columns of switches 100, and an uplink optical fiber 136 that receives light from switches 100'. Switch 100'a is specific to light of wavelength  $\lambda_1$ , and directs light of wavelength  $\lambda_1$ , emerging from switches 100aa and 100ba, towards uplink optical fiber 136. Similarly, switch 100'b is specific to light of wavelength  $\lambda_2$ , and directs light of wavelength  $\lambda_2$ , emerging from switches 100ab and 100bb, towards uplink optical fiber 136. Common output optical fiber 106 wraps around to become an input optical fiber 134 for switches 100'. Thus, the light entering device 140 from input optical fiber 102 at wavelengths other than  $\lambda_1$  and  $\lambda_2$  is merged with the light of wavelengths  $\lambda_1$  and  $\lambda_2$  that is not diverted to output optical fibers 104, and uplink 136 serves as the actual common output optical fiber of device 140.

In an embodiment of the basic device of the present invention that includes the features of both embodiment 120 of Figure 3 and embodiment 140 of Figure 5, the voltages applied to switches 100' direct only a portion of the light that emerges from their respective columns of switches 100 to uplink optical fiber 136. The rest of this light is detected by detectors such as detectors 114.



Figure 6 is a schematic illustration of a compound device 150 of the present invention, based on two modules, a module 110' that is almost identical to device 110, and a module 120' that is similar to device 120, but lacks filters 112, beamsplitters 116 and detectors 118. Module 110' includes two switches, 100aa and 100ba, for switching light of wavelength  $\lambda_1$ , and two switches, 100ab and 100bb, for switching light of wavelength  $\lambda_2$ . Module 120' includes two switches, 100ca and 100da, for switching light of wavelength  $\lambda_1$ , and two switches, 100cb and 100db, for switching light of wavelength  $\lambda_2$ . As in device 110, switches 100aa and 100ab divert a portion of their respective inputs to output optical fiber 104a, and switches 100ba and 100bb divert a portion of their respective inputs to output optical fiber 104b. Similarly, switches 100ca and 100cb divert a portion of their respective inputs to an output optical fiber 104c, and switches 100da and 100db divert a portion of their respective inputs to an output optical fiber 104d. Switches 100aa and 100ba are coupled optically to switches 100ca and 100da by an intermediate optical fiber 142a. Similarly, switches 100ab and 100bb are coupled optically to switches 100cb and 100db by an intermediate optical fiber 142b. Optionally, switches 100 of module 110' are coupled to switches 100 of module 120' across free space, without the intervention of intermediate optical fibers 142. Thus, device 150 functions as a basic device of the present invention with double the number of output optical fibers 104.

Figure 7 is a schematic illustration of a compound device 160 of the present invention based on two devices 140 used as modules. Uplink optical fiber 136 of the left hand module 140 leads into input optical fiber 102 of the right hand module 140 to provide input to the right hand module 140. As in device 140 of Figure 5, filters 112 of the left hand module 140 divert light of wavelengths  $\lambda_1$  and  $\lambda_2$ , respectively. Filters 112 of the right hand module 140 divert light of two other wavelengths,  $\lambda_3$  and  $\lambda_4$ , respectively. Thus, device 160 functions as a basic device of the present invention that switches twice as many data streams to twice as many output optical fibers 104.

Figure 8 is a schematic illustration of a compound device 170 of the present invention based on two modules, 140' and 140'', that are almost identical to device 140. Module 140' includes a wavelength-specific filter 112a that diverts light of wavelength  $\lambda_1$  to two switches, 100aa and 100ba, and wavelength-specific filter 112b

that diverts light of wavelength  $\lambda_2$  to two switches, 100ab and 100bb. Switches 100aa and 100ab divert part or all of the light they receive to an intermediate optical fiber 164a. Switches 100ba and 100bb divert part or all of the light they receive to an intermediate optical fiber 164b. Light not diverted by filters 112a and 112b is  
5 conducted by an intermediate optical fiber 162 to module 140'', where a wavelength-specific filter 112c diverts light of wavelength  $\lambda_3$  to two switches, 100ac and 100bc, and a wavelength-specific filter 112d diverts light of wavelength  $\lambda_4$  to two switches, 100ad and 100bd. Switches 100ac and 100ad divert part or all of the light they receive to output optical fiber 104a. Switches 100bc and 100bd divert part or all  
10 of the light they receive to output optical fiber 104b. Light not diverted by filters 112c and 112d enters common output optical fiber 106. Intermediate optical fiber 164a couples filters 100aa and 100ab optically to filters 100ac and 100ad, and the light diverted by filters 100aa and 100ab to filters 100ac and 100ad via intermediate optical fiber 164a passes through filters 100ac and 100ad to output optical fiber 104a.  
15 Similarly, intermediate optical fiber 164b couples filters 100ba and 100bb optically to filters 100bc and 100bd, and the light diverted by filters 100ba and 100bb to filters 100bc and 100bd via intermediate optical fiber 164b passes through filters 100bc and 100bd to output optical fiber 104b. As in device 140, common output optical fiber 106 wraps around to become input optical fiber 134, and light received by module  
20 140' from input optical fiber 134 joins light not diverted by filters 100aa, 100ba, 100ab and 100bb to be directed by electroholographic switches 100'a and 100'b to an intermediate optical fiber 166. In module 140'', light received from intermediate optical fiber 166 joins light not diverted by filters 100ac, 100bc, 100ad and 100bd to be directed by electroholographic switches 100'c and 100'd to uplink optical fiber  
25 136. Thus, device 170 functions as a basic device of the present invention that switches twice as many data streams to the same number of output optical fibers.

Figure 9 illustrates, schematically, an alternative way to couple modules 140' and 140'' to produce a compound device 180 of the present invention. Intermediate optical fibers 164, instead of being optically coupled to filters 100 of module 140'',  
30 are coupled directly to output optical fibers 104 at y-junctions 172a and 172b. In addition, uplink optical fibers 136 of modules 140' and 140'' are mutually coupled at

y-junction 172c. Thus, device 180 emulates a basic device of the present invention that switches twice as many data streams to the same number of output optical fibers.

Figure 10 is a schematic illustration of a compound device 190 of the present invention based on three devices 110 used as modules. All three output optical fibers 104a lead to a multiplexer 182a, which receives the data streams that are switched in devices 110 to output optical fibers 104a and combines these data streams into a combined data stream on a common output optical fiber 184a. Similarly, all three output optical fibers 104b lead to a multiplexer 182b, which receives the data streams that are switched in devices 110 to output optical fibers 104b and combines these data streams into a combined data stream on a common output optical fiber 184b. Device 190 serves as a 3 x 2 x 2 optical cross-connect, that cross-connects two wavelengths from three inputs to two outputs.

Figure 11 is a schematic illustration of a compound device 220 of the present invention based on two modules 110'' and 110'''. Module 110'' is almost identical to device 110. In module 110'', wavelength-specific filter 112a diverts light of wavelength  $\lambda_1$  to two switches 100aa and 100ba, and wavelength-specific filter 112b diverts light of wavelength  $\lambda_2$  to two switches 100ab and 100bb. Switches 100aa and 100ab divert all or part of the light they receive to a transponder 222a. In general, a transponder is a receiver-transmitter device that automatically transmits a signal when the proper interrogating signal is received. In this case, transponder 222a reshapes, regenerates and optionally retimes the signals it receives and outputs those signals using a carrier wave of a wavelength  $\lambda_3$  different from either  $\lambda_1$  or  $\lambda_2$ . Similarly, switches 100ba and 100bb divert all or part of the light they receive to a transponder 222b that reshapes, regenerates and optionally retimes the signals it receives and outputs those signals using a carrier wave of a wavelength  $\lambda_4$  different from either  $\lambda_1$  or  $\lambda_2$  or  $\lambda_3$ . Module 110''' is similar to device 110, but lacks wavelength-specific filters 112. Instead, light emerging from transponder 222a traverses a column of switches 100ac, 100ad and 100ae that are specific to light of wavelength  $\lambda_3$ , and light emerging from transponder 222b traverses a column of switches 100bc, 100bd and 100be that are specific to light of wavelength  $\lambda_4$ . Switches 100ac and 100bc divert all or part of the light they receive to output optical fiber 104c; switches 100ad and

100bd divert all or part of the light they receive to output optical fiber 104d; and switches 100ae and 100be divert all or part of the light they receive to output optical fiber 104e. Note that the order of the rows and columns of switches 100 in module 110''', as drawn in Figure 11, is transposed relative to the order of the rows and columns of switches 100 in module 110''. As in basic embodiment 140, common  
5 output optical fiber 106 of module 110'' serves as an input optical fiber 134 of module 110''' for the purpose of uplink.

As in basic embodiment 120 of Figure 3, the columns of module 110'' and the rows of module 110''' terminate in detectors 114 and 115 that typically are integrated  
10 in electronic devices that perform system functions such as error detection, network monitoring and analysis, and data monitoring and analysis.

The purpose of device 220 is wavelength conversion. In this application, module 110'' must be operated only in cross-connect mode, and not in broadcast or multicast mode: only one switch 100 per column and only one switch 100 per row.  
15 may be activated. The wavelength conversion is determined by which switches 100 are activated. If switches 100aa and 100bb are activated, then part or all of the data stream of carrier wavelength  $\lambda_1$  is converted to a data stream of carrier wavelength  $\lambda_3$ , and part or all of the data stream of carrier wavelength  $\lambda_2$  is converted to a data stream of carrier wavelength  $\lambda_4$ . Similarly, if switches 100ab and 100ba are activated, then  
20 part or all of the data stream of carrier wavelength  $\lambda_1$  is converted to a data stream of carrier wavelength  $\lambda_4$ , and part or all of the data stream of carrier wavelength  $\lambda_2$  is converted to a data stream of carrier wavelength  $\lambda_3$ . Module 110''' effects cross-connect, broadcast and multicast of the data streams of carrier wavelengths  $\lambda_3$  and  $\lambda_4$ .

25 Figure 12 is a schematic illustration of an electroholographic tap 200 of the present invention, used to equalize the powers of channels of carrier wavelengths  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$ , propagating to the right in a common optical conduit such as an optical fiber 206, after these channels have been amplified by an amplifier 202 such as an erbium-doped fiber amplifier. Such equalization is needed because amplifier 202  
30 typically has a response that is not flat as a function of wavelength. Therefore, even if the three channels have the same power upon entry to amplifier 202, these channels

may have different powers upon emerging from amplifier 202. Electroholographic tap 200 includes three electroholographic switches 100, each specific to one of the three wavelengths  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$ , and three detectors 210 that are similar to detectors 114. A portion of the light of wavelength  $\lambda_1$  entering tap 200 is diverted by switch 100a to  
5 detector 210a, a portion of the light of wavelength  $\lambda_2$  entering tap 200 is diverted by switch 100b to detector 210b, and a portion of the light of wavelength  $\lambda_3$  entering tap 200 is diverted by switch 100c to detector 210c. The remainder of the light entering tap 200 from the left exits tap 200 to the right and continues to propagate in optical fiber 206.

10 Also shown in Figure 12 is a control module 212, for power equalization, that receives electronic signals from detectors 210 and applies control voltages to switches 100. The combination of detectors 210 and control module 212 provides a feedback loop for equalizing the power of the channels of carrier wavelengths  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$ . Control module 212 receives electrical signals from detectors 210 that are  
15 representative of the intensities of the light diverted to detectors 210 by switches 100. Control module 212 then adjusts the voltages applied to switches 100 to equalize the powers of the channels of carrier wavelengths  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  in optical fiber 206.

Figure 13 is a schematic illustration of an add-drop multiplexer 230 of the present invention. Add-drop multiplexer 230 is based on two modules, a drop module  
20 231 that is identical to device 140, and an add module 234. The purpose of add-drop multiplexer is to remove, from the plurality of concurrent WDM data streams coming in on input optical fiber 102, the data streams having carrier wavelengths  $\lambda_1$  and  $\lambda_2$ , and to substitute for these two data streams two other data streams having carrier wavelengths  $\lambda_1$  and  $\lambda_2$ . Output optical fibers 104a and 104b serve as diversion  
25 conduits: the input data streams having carrier wavelengths  $\lambda_1$  and  $\lambda_2$  are diverted to either or both of output optical fibers 104a and 104b by drop module 231.

The remaining data streams proceed via uplink optical fiber 136 to add module 234. Also input to add module 234 are two substitution data streams, one having carrier wavelength  $\lambda_1$  and the other having carrier wavelength  $\lambda_2$ . The substitution  
30 data stream having carrier wavelength  $\lambda_1$  is introduced to add module 234 via an input optical fiber 236a functioning as a substitution conduit. The substitution data stream

having carrier wavelength  $\lambda_2$  is introduced to add module 234 via an input optical fiber 236b functioning as a substitution conduit.

Add module 234 includes two optical components 232a and 232b that merge the data streams having carrier wavelengths  $\lambda_1$  and  $\lambda_2$ , and that enter add module 234 via input optical fibers 236, with the data streams that enter add module 234 via uplink optical fiber 236. The two substitution data streams are merged with the other data streams by optical components 232, and all the data streams input to add module 234 emerge via an extension 240, of uplink optical fiber 136, that functions as the output conduit of add-drop multiplexer 230.

Three implementations of optical components 232 are possible. In the first implementation, optical components 232 are y-junctions, similar to y-junctions 172 of device 180 of Figure 9. In the second implementation, optical components 232 are wide-band electroholographic switches. In the third implementation, optical components 232 are narrow-band electro-optical switches such as electroholographic switches 100.

Under the second and third implementations of optical components 232, uplink optical fiber 136 is coupled optically to components 232 in the same way that input optical fiber 136 of Figure 5 is coupled optically to electroholographic switches 100'; input optical fiber 236a is coupled optically to component 232a in the same way that switches 100aa and 100ba are coupled optically to electroholographic switch 100'a of Figure 5; and input optical fiber 236b is coupled optically to component 232b in the same way that switches 100ab and 100bb are coupled optically to electroholographic switch 100'b of Figure 5. Under the second implementation of optical components 232, each of input optical fibers may carry several data streams of several carrier wavelengths (e.g.,  $\lambda_{1a}$ ,  $\lambda_{1b}$ , etc. on input optical fiber 236a and  $\lambda_{2a}$ ,  $\lambda_{2b}$ , etc. on input optical fiber 236b), depending on the bandwidths of wide-band electro-optical switches 232, as long as the two sets of carrier wavelengths are disjoint.

Preferably, under the second and third implementations of optical components 232, drop module 231 includes the features of both device 140 and device 120. Wide or narrow band electro-optic switches 232 divert only a portion of the light from their

respective input optical fibers 236 to extension 240. The light not diverted by switches 232 is detected by detectors 238 that are similar to detectors 114 and 118, and the electrical signals from detectors 114, 118 and 238 are used by a control system to adjust the voltages applied to electroholographic switches 100 of drop module 231 and to electro-optic switches 232, in order to equalize the power of the substitution data streams with the power of the data streams they replace.

It will be appreciated that add module 234 may serve as multiplexer 182 of device 190 of Figure 10.

Figure 14 is a schematic illustration of an alternative add module 234' of the present invention. Add module 234' combines features of basic embodiments 120 and 140 of Figures 3 and 5 to provide, in one device, the separate advantages of the second and third implementations of add module 234. Both input optical fiber 236a and input optical fiber 236b carry substitution data streams of both carrier wavelengths  $\lambda_1$  and  $\lambda_2$ . Controllable portions of these data streams are directed to electroholographic switches 100'a and 100'b by electroholographic switches 100aa, 100ab, 100ba and 100bb. The remainder of the substitution data streams continue to propagate rightward to be discarded, or to be detected for network management purposes by detectors (not shown) that are similar to detectors 114. Switches 100'a and 100'b merge a controllable portion of the data streams incident thereon from below with the data streams entering from the left via uplink optical fiber 236, and the merged data streams exit rightward via extension 240. The portions of the data streams incident on switches 100'a and 100'b from below, that are not merged with the data streams entering via uplink optical fiber 136 from the right, are detected by detectors 238'a and 238'b, respectively that are similar to detectors 238; and the resulting electronic signals are used for network management functions such as power equalization.

Figure 15 illustrates an alternate method of implementing power equalization in add-drop multiplexer 230. An output optical fiber 104 of drop module 231 and a corresponding input optical fiber 236 of add module 234 are provided with respective electroholographic taps 200' and 200'' that share a common control module 212 that receives electronic signals from the detectors of taps 200' and 200'' and that controls

the voltages applied to the electroholographic switches of taps 200' and 200''. From the signals received from the detectors of tap 200', control module 212 infers the power levels of the data streams in output optical fiber 104. Control module then adjusts the voltages applied to the electroholographic switches of tap 200'', with  
5 feedback from the detectors of tap 200'', to make the power levels of the substitution data streams in input optical fiber 236 equal to the power levels of the corresponding data streams in output optical fiber 104.

The scope of the present invention also includes electroholographic switches in which the paraelectric photorefractive crystals 10 or 11 include several superposed  
10 holographic gratings 17 or 19, each grating 17 or 19 having a different spacing, for switching light of several different wavelengths according to the Bragg condition. Figure 1 serves to illustrate these kinds of switches, with the understanding that reference numerals 17 and 19 indicate, not single holographic gratings, but several  
superposed holographic gratings. Note that all the superposed gratings are activated  
15 together by the same voltage difference across the same electrode pair 12, 14 or 13, 15. Such switches provide an alternative to switches 100 of device 130. Specifically, each alternative electroholographic switch is fabricated with two holographic gratings 17 or 19 per crystal 10 or 11, each grating having a different spacing. One of the gratings is used to implement the switching function of the electroholographic  
20 switches, *i.e.*, the switching of light of wavelength  $\lambda_1$  or  $\lambda_2$ . The other grating is used to divert a beam 126, to an extent proportional to the extent to which the data stream of carrier wavelength  $\lambda_1$  or  $\lambda_2$  is diverted to an output optical fiber 104. This alternative allows more flexibility in the positioning of detectors 124 relative to their  
respective electroholographic switches.

25 Figures 16A and 16B are schematic side and front views, respectively, of electroholographic switches 100aa and 100ba fabricated in and on a single photorefractive crystal 250. Switch 100aa includes a holographic grating 17aa, within crystal 250, sandwiched between two electrodes 12aa and 14aa on opposite surfaces 252 and 254 of crystal 250, and a holographic grating 19aa, within crystal  
30 250, sandwiched between two electrodes 15aa and 13aa on opposite surfaces 252 and 254 of crystal 250. Similarly, switch 100ba includes a holographic grating 17ba,



within crystal 250, sandwiched between two electrodes 12ba and 14ba on opposite surfaces 252 and 254 of crystal 250, and a holographic grating 19ba, within crystal 250, sandwiched between two electrodes 15ba and 13ba on opposite surfaces 252 and 254 of crystal 250. It has been found that the electric field established across grating 17aa, 19aa, 17ba or 19ba by the voltage difference applied to its respective electrode pairs 12aa-14aa, 13aa-15aa, 12ba-14ba and 13ba-15ba, is confined to the vicinity of that grating 17aa, 19aa, 17ba or 19ba, and does not cause cross-talk with the other gratings. Preferably, to ensure that there is no cross-talk among the gratings, the polarities of successive electrode pairs are alternated, as shown: the successive electrodes on surface 252 are grounded electrode 15aa, active electrode 12aa, grounded electrode 15ba and active electrode 12ba; and the successive electrodes on surface 254 are active electrode 13aa, grounded electrode 14aa, active electrode 13ba and grounded electrode 14ba. The term "active electrode" is used herein to refer to the electrode to which voltage V, relative to ground, is applied, as illustrated in Figure 1.

For illustrational simplicity, Figure 16 shows only a single column of switches 100 of device 110 fabricated in a single crystal 250. It will be appreciated that all four switches 100 of device 110 could be fabricated in a single photorefractive crystal, as a two dimensional array of switches 100. It also will be appreciated that in an embodiment of device 110 in which filters 112 are implemented as electroholographic switches, filters 112 also could be fabricated in the same photorefractive crystal as switches 100.

In an alternative embodiment of switches 100aa and 100ba, electrodes 12 and 14 are deposited on the same side of crystal 250 and, electrodes 13 and 15 are deposited on the same side (not necessarily the side on which electrodes 12 and 14 are deposited) of crystal 250.

In addition to the various embodiments of the devices of the present invention for a wavelength specific photonic switch, several management devices are contemplated as being within the scope of the present invention. These management devices enable the residual portion of the original, or undiverted, signal to be analyzed, for network management purposes such as error detection for the optical

signal. Preferred embodiments of these management devices are illustrated in Figures 17-21, including a preferred detection module and exemplary output according to the present invention (Figure 17); a preferred optical signal power level determiner according to the present invention (Figure 18); and three preferred embodiments of the management analyzer according to the present invention (Figures 19-21). It is to be understood that although reference is made specifically to the wavelength specific photonic switching devices described in Figures 1-14 above, the management devices of Figures 17-21 could also optionally be used with other types of optical switching devices. Each of these management devices is able to determine a quality characteristic of the optical signal, as described in greater detail below.

Figure 17 is a schematic block diagram of an illustrative detection module according to the present invention. A detection module 300 according to the present invention is in communication with an electro-optical switch according to the present invention, such as any of the electro-optical switches of Figures 1-14 for example. A switch interface 302 receives a residual signal from the electro-optical switch (not shown), which has split off this portion of the optical signal for analysis. Switch interface 302 then passes the residual signal to a photo-detector 304. Optionally and preferably, switch interface 302 is connected to a plurality of photo-detectors 304, each photo-detector 304 corresponding to a specific wavelength if the electro-optical switch is a wavelength specific switch.

Each photo-detector 304 converts the received light from the residual signal into a voltage. The voltage is then passed to each of a plurality of voltage comparators, including a high voltage comparator 306 and a low voltage comparator 308 as shown. High voltage comparator 306 and low voltage comparator 308 are collectively an example of an analyzer according to the present invention. High voltage comparator 306 compares the received voltage to a maximum preset high threshold. If the received voltage is greater than this high voltage threshold, then a high voltage indication is generated by high voltage comparator 306. The high voltage indication indicates that the level of the input signal of the switching core is saturated, such that this saturation is a quality characteristic of the optical signal.

For example, high voltage comparator 306 could cause an LED to become lit.

As another example, high voltage comparator 306 could send such a high voltage indication to a host interface 309. Host interface 309 preferably features a first electronic hardware input 310 for receiving the high voltage signal from high voltage comparator 306. This high voltage signal is the digital result of the comparison for determining the high power indication. Host interface 309 also preferably features an output alarm module 312 for notification of a system manager or other component of the network when the high voltage indication has been received. Output alarm module 312 is optionally implemented as software, hardware or firmware, or a combination thereof.

Similarly, low voltage comparator 308 compares the received voltage to a minimum preset low threshold. If the received voltage is less than this low voltage threshold, then a low voltage indication is generated by low voltage comparator 308. The low voltage indication indicates that the level of the input signal to the optical switching core is below the minimum value, such that this low level is a quality characteristic of the optical signal. As for high voltage comparator 306 above, such low voltage comparator 308 could cause an LED to become lit, or alternatively low voltage comparator 308 could send such a low voltage indication to host interface 309. Host interface 309 preferably features a second electronic hardware input 314 for receiving the low voltage signal from high voltage comparator 306. Host interface 309 also preferably features an output alarm module 312 for notification of a system manager or other component of the network when the high voltage indication has been received.

Preferably, host interface 309 is able to configure the high and low voltage detection thresholds for high voltage comparator 306 and low voltage comparator 308, respectively. The threshold is defined by setting the level of the reference voltage to the comparator. This reference voltage can be provided by a variable resistor or D/A. More preferably, host interface 309 is able to receive configuration instructions from an outside source, such as a system manager (not shown), for determining how to configure these thresholds. For example, the system manager could optionally request host interface 309 to decrease the threshold of high voltage comparator 306 and/or to increase the threshold for low voltage comparator 308, for more precise control of the

optical signal. Of course, the threshold for only one of high voltage comparator 306 and/or low voltage comparator 308 could also optionally be adjusted.

Figure 18 is a schematic block diagram of an optical signal power level determiner according to the present invention. A signal power level determiner 316 again is in communication with an electro-optical switch according to the present invention, such as any of the electro-optical switches of Figures 1-14 for example. Signal power level determiner 316 is in communication with switch interface 302, which may be the same or different than the switch interface of Figure 17. Switch interface 302 again receives a residual signal from the electro-optical switch (not shown), which has split off this portion of the optical signal for analysis. Switch interface 302 then passes the residual signal to a transistor 318. Transistor 318 translates the received residual light signal to voltage. The voltage is then converted into a digital signal by an A/D (analog to digital) converter 320, with the resolution determined according to the requirements of the system. Transistor 318 and A/D converter 320 are collectively another example of an analyzer according to the present invention.

The digital value of the power the received light signal is latched into a per channel register 322, such that this power is a quality characteristic of the optical signal. The value from register 322 is then transferred to host interface 309, and then to the host (not shown) upon request by the host. The host request includes the command itself from the host, which specifies the number of the selected channel or selected wavelength. The information is selected (not shown), and is transferred to the host.

Optionally and preferably, signal power level determiner 316 also features a configurable threshold indicator (not shown) as for detection module 300 of Figure 17. The configurable threshold indicator would compare the received digital values to a predefined high threshold and to a predefined low threshold, and would then more preferably generate both the same alarm indication and/or status register as necessary. Most preferably, the threshold indicator is fully configurable, as such configurability is essential for fine adjustments of the power monitoring and detection of small deviations from the expected power levels for the optical signal.

Optionally, both A/D (analog to digital) converter 320 and the threshold converter are implemented as a DSP or as an analog ASIC chip. Optionally, the output of the detector can be used as input for error detection using a dedicated device for SONET/SDH data overhead monitor.

5            Optionally, the output of the detector is used to determine the data rate and protocol using a dedicated device for clock and data recovery.

             Figures 19-21 show three different preferred embodiments of exemplary management analyzers according to the present invention. Each such management analyzer is able to analyze the optical signal in order to assess signal quality and to  
10            perform error detection, in order to determine a quality characteristic of the optical signal. Although the following description centers upon the analysis of the optical signal for the physical layer (layer 1) of the networking model, it is understood that such analysis could also be used for higher level protocols and data structures, such as for IP packets (layer 3) transmitted over the network.

15            Figure 19 shows a first embodiment of an exemplary management analyzer 324 according to the present invention. In this embodiment, management analyzer 324 is dedicated to a particular wavelength of optical signal. Management analyzer 324 again is in communication with an electro-optical switch, or tap, according to the present invention, such as any of the electro-optical switches of Figures 1-14 for  
20            example. Such communication is effected through switch interface 302, which again may be the same or different than the switch interface of Figures 17 or 18. Switch interface 302 again receives a residual signal from the electro-optical switch (not shown), which has split off this portion of the optical signal for analysis. Switch interface 302 then passes the residual signal to a receiver 326, which converts the  
25            optical signal to an electronic digital signal, preferably as well as performing the clock recovery with a clock 328. In this embodiment, receiver 326 is dedicated to a single wavelength of light. The serial (single bit) electronic signals are translated into a parallel format of 8, 16 or 32 bit signals by a data translator 330. Receiver 326, clock 328 and data translator 330 are collectively yet another example of an analyzer  
30            according to the present invention.

             The translated data is then passed to an analysis engine 332. Analysis engine

332 performs any necessary statistical analyses on the translated data in order to assess the optical signal. For example, analysis engine 332 could determine the available bandwidth by assessing the relative frequency of high threshold power overload, as such an overload indicates saturation of the electro-optical switch and hence of the network. In addition, analysis engine 332 could calculate the relative variation in the optical signal, which is an assessment of the control of signal transduction through the optical network and which is another quality characteristic of the optical signal.

According to a preferred embodiment of analysis engine 332, the information which is collected about the optical signal is relatively simple, such as information provided by traffic counters for example. Such information is more preferably supplied to the host through host interface 309, and is then retrieved at a predefined sampling rate. Preferably, the recovered clock is used for identification of the data rate. Optionally and preferably, analysis engine 332 is constructed as a combination of DSP, CPU and ASIC chips and/or firmware, in order to provide data analysis with a sustained rate of at least 2.5 Gbps. Optionally and more preferably, analysis engine 332 is shared by a plurality of receivers 326 for receiving light of a plurality of different wavelengths for the optical signal.

Figure 20 shows a second embodiment of an exemplary management analyzer according to the present invention. In this embodiment an exemplary management analyzer 334 is again connected to switch interface 302, as for the embodiment shown in Figure 19. However, management analyzer 334 now features a single receiver 336, connected to an optical channel selector 338. Optical channel selector 338 selects an optical channel and directs light of that wavelength to receiver 336. Preferably, optical channel selector 338 selects light from each channel in turn, in a "round robin" selection. Optionally and more preferably, optical channel selector 338 is configurable, for example through instructions from the host (not shown) through host interface 309. The remaining components of management analyzer 334, including clock 328, data translator 330 and analysis engine 332, are implemented as for Figure 19. Optionally and preferably, the optical channel selector is an ELECTROHOLOGRAPHIC switch.

Figure 21 shows a third exemplary embodiment of a management analyzer

according to the present invention, with a mixed configuration which permits both single channel selection for optical signal analysis and continuous optical signal monitoring. Optionally, the analyzer incorporates functionality for power level monitoring. Optionally and more preferably, functionality for error detection is also  
5 featured. A management analyzer 340 is again connected to switch interface 302, as for the embodiment shown in Figures 19 and 20. As for Figure 20, management analyzer 340 again features single receiver 336 connected to optical channel selector 338. Optical channel selector 338 again selects an optical channel and directs light of that wavelength to receiver 336. Other components of management analyzer 340,  
10 including host interface 309, clock 328, data translator 330 and analysis engine 332, are implemented as for Figures 19 and 20.

In order to provide the continuous optical signal monitoring, management analyzer 340 features a photodetector 342, which converts the received optical signal into a digital voltage signal for further analysis. Preferably, analysis engine 332 is  
15 able to detect any alterations in the power level out of an acceptable range, whether above or below that range. Optionally and more preferably, such detection is used to identify the data rate and detect data errors, which are further examples of quality characteristics of the optical signal. More preferably, such detection is coupled to threshold analysis, such that if the optical signal passes out of the acceptable range, an  
20 alarm is sounded. Most preferably, analysis engine 332 is able to include an estimate of optical attenuation caused by the optical switch, for a more accurate determination of the power level of the optical signal.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other  
25 applications of the invention may be made.

## WHAT IS CLAIMED IS:

1. A device for switching light of any of a plurality of discrete wavelengths to any of a plurality of output conduits, comprising:
  - (a) for each wavelength and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength being optically coupled.
2. The device of claim 1, further comprising:
  - (b) for each wavelength, a mechanism for diverting the light of said each wavelength to said respective electroholographic switches while passing the light of all other wavelengths.
3. The device of claim 2, wherein said mechanism includes a filter.
4. The device of claim 3, wherein each said electroholographic switches includes at least one photorefractive crystal including a grating specific to said wavelength that is switched by said each electroholographic switch.
5. The device of claim 4, wherein said grating is stored in said crystal as a hologram.
6. The device of claim 4, wherein said photorefractive crystal includes a photorefractive material selected from the group consisting of potassium tantalate niobate, strontium barium niobate and potassium lithium tantalate niobate.
7. The device of claim 6, wherein said photorefractive crystal includes potassium lithium tantalate niobate doped with copper and vanadium.



8. The device of claim 4, wherein each said grating effects said switching at an angle substantially equal to  $90^\circ$ .

9. The device of claim 1, further comprising:

(b) for each of at least a portion of the wavelengths, a detector for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits.

10. The device of claim 9, wherein said detector further comprises:

(i) a switch interface for connecting to said electroholographic switch and for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits; and

(ii) an analyzer for receiving an optical signal from said switch interface according to the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits and for converting said optical signal to a voltage for analysis.

11. The device of claim 10, wherein said analyzer further comprises:

(1) a photo-detector for receiving said optical signal from said switch interface and for converting said optical signal to said voltage;

(2) a high threshold voltage comparator for comparing said voltage to a high voltage threshold, such that if said voltage is higher than said high voltage threshold, a high voltage indication is indicated; and

(3) a low threshold voltage comparator for comparing said voltage to a low voltage threshold, such that if said voltage is lower than said low voltage threshold, a low voltage indication is indicated.

12. The device of claim 11, wherein at least one of said low voltage indication and said high voltage indication is an LED.

13. The device of claim 12, wherein the device is in communication with a host and wherein the device further comprises a host interface for transmitting information to said host, such that at least one of said low voltage indication and said high voltage indication is an alarm indication for transmitting to said host.

14. The device of claim 10, wherein the device is in communication with a host and wherein the device further comprises a host interface for transmitting information to said host, and wherein said analyzer further comprises:

- (1) a transistor for receiving the optical signal from said switch interface and for converting the optical signal to said voltage; and
- (2) an analog to digital (A/D) converter for converting said voltage to a digital signal and for transmitting said digital signal to said host through said host interface.

15. The device of claim 14, wherein said A/D converter transmits said digital signal to said host upon receiving a request from said host through said host interface.

16. The device of claim 9, wherein said detector further comprises:

- (i) a switch interface for connecting to said electroholographic switch and for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits; and
- (ii) a management analyzer for analyzing at least one wavelength of the optical signal to determine a quality of the optical signal.

17. The device of claim 16, wherein said optical signal is comprised of a plurality of wavelengths and said detector further comprises an electroholographic switch for switching one of said plurality of wavelengths of said optical signal to said management analyzer.

18. The device of claim 17, wherein said management analyzer further comprises:

- (1) at least one receiver for receiving a single wavelength of said optical signal and for converting said single wavelength of said optical signal to a digital signal; and
- (2) an analysis engine for analyzing said digital signal to determine said quality of said optical signal.

19. The device of claim 18, wherein said digital signal from said receiver is a serial digital signal and said management analyzer further comprises:

- (3) a data translator for translating said serial digital signal to a parallel digital signal, and for passing said parallel digital signal to said analysis engine.

20. The device of claim 17, wherein said management analyzer further comprises:

- (1) an optical signal wavelength selector for selecting a wavelength of said optical signal;
- (2) a single receiver for receiving said wavelength of said optical signal and for converting said wavelength of said optical signal to a digital signal; and
- (3) an analysis engine for analyzing said digital signal to determine said quality of said optical signal.

21. The device of claim 20, wherein said management analyzer further comprises:

- (4) a photo-detector for monitoring a power of said optical signal from said optical signal wavelength selector.

22. The device of claim 20, wherein said optical signal wavelength selector is an electroholographic switch.

23. The device of claim 1, further comprising:
- (b) for each wavelength, a mechanism for diverting, to an uplink conduit, the light of said each wavelength remaining after said controllable portion of the light of said each wavelength is switched to the output conduits.

24. The device of claim 23, wherein said mechanism for diverting said remaining light to said uplink conduit includes an electroholographic switch.

25. The device of claim 1, wherein at least one of said output conduits includes a transponder for receiving said controllable portions of the light that is switched to said at least one output conduit and emitting corresponding light of a single output wavelength.

26. The device of claim 1, further comprising:
- (b) for each of at least a portion of the output conduits:
    - (i) a detector; and
    - (ii) a mechanism for diverting, to said detector, a subportion of each said controllable portion of the light that is switched to said each output conduit.

27. The device of claim 26, wherein said mechanism for diverting said subportion includes a component selected from the group consisting of beamsplitters and electroholographic switches.

28. The device of claim 1, further comprising:
- (b) for each of at least a portion of said wavelengths:
    - (i) a light source emitting light of a wavelength other than said each wavelength; and
    - (ii) for each said output conduit, a detector for receiving said light of said other wavelength from said

electroholographic switch that switches said controllable portion of said light of said each wavelength to said each output conduit.

29. A method for switching light of any of a plurality of discrete wavelengths to any of a plurality of output conduits, comprising the steps of:

- (a) providing, for each wavelength and for each output conduit, a respective electroholographic switch;
- (b) for each wavelength, diverting the light of said each wavelength to said electroholographic switches of said each wavelength; and
- (c) for each said electroholographic switch, setting a state of said each switch so as to further divert a desired portion of the light of said respective wavelength of said each switch to said respective output conduit of said each switch.

30. The method of claim 29, wherein said setting of said state of said each switch is effected by applying to said each switch a voltage effective to further divert said desired portion of the light of said respective wavelength of said each switch to said respective output conduit of said each switch.

31. The method of claim 29, further comprising the steps of:

- (d) for each wavelength, measuring an intensity of the light of said each wavelength remaining after said desired portions of the light of said each wavelength are diverted to the output conduits; and
- (e) adjusting said voltages based on said measured intensities.

32. The method of claim 29, further comprising the step of:

- (d) for each output conduit, verifying that said desired portion of each wavelength has been diverted to said each output conduit.

33. The method of claim 32, wherein said verifying is effected by steps including, for each output conduit:

- (i) diverting a subportion of each said desired portion of the light that is diverted to said each output conduit; and
- (ii) measuring an intensity of said subportion.

34. The method of claim 32, wherein said verifying is effected by steps including, for each wavelength:

- (i) directing light of a wavelength other than said each wavelength at said respective electroholographic switches; and
- (ii) for each output conduit, measuring an intensity of said light of said wavelength other than said each wavelength that is diverted by said respective electroholographic switch.

35. A device for switching light of any of a plurality of discrete wavelengths to any of a first and second pluralities of output conduits, comprising:

- (a) a first module including:
  - (i) for each wavelength and for each output conduit of the first plurality, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit of the first plurality, said electroholographic switches of a common output conduit of the first plurality being optically coupled, said electroholographic switches of a common wavelength being optically coupled; and
- (b) a second module including:
  - (i) for each wavelength and for each output conduit of the second plurality, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit of the second plurality, said electroholographic switches of a common output conduit of the second plurality being optically coupled, said electroholographic switches of a common wavelength being optically coupled.

36. The device of claim 35, wherein said first module further includes:

(ii) for each wavelength, a mechanism for diverting the light of said each wavelength to said respective electroholographic switches while passing the light of all other wavelengths;

37. The device of claim 35, wherein, for each said wavelength, said respective electroholographic switches of said second module are optically coupled to said respective electroholographic switches of said first module.

38. A device for switching light of any of a first and second pluralities of discrete wavelengths to any of a first and second pluralities of output conduits, comprising:

(a) an uplink conduit;

(b) a first module including:

(i) for each wavelength of the first plurality of wavelengths and for each output conduit of the first plurality of output conduits, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength being optically coupled, and

(ii) for each wavelength of the first plurality, a mechanism for diverting, to said uplink conduit, the light of said each wavelength remaining after said controllable portion of the light of said each wavelength is switched to the first plurality of output conduits; and

(c) a second module including:

(i) for each wavelength of the second plurality of wavelengths and for each output conduit of the second plurality of output conduits, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said

each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength being optically coupled, and

- (ii) for each wavelength of the second plurality, a mechanism, optically coupled to said uplink conduit, for diverting the light of said each wavelength to said respective electroholographic switches while passing the light of all other wavelengths.

39. A device for switching light of any of a first and second pluralities of discrete wavelengths to any of a plurality of output conduits, comprising:

- (a) a first module including:
  - (i) for each wavelength of the first plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the first plurality to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength of the first plurality being optically coupled; and
- (b) a second module including:
  - (i) for each wavelength of the second plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the second plurality to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength of the second plurality being optically coupled.

40. The device of claim 39, wherein each said module further includes, for



each wavelength of the respective plurality:

- (ii) a mechanism for diverting the light of said each wavelength of said respective plurality to said respective electroholographic switches while passing the light of all other wavelengths.

41. The device of claim 39, wherein, for each output conduit, said respective electroholographic switches of said first module are optically coupled to said respective electroholographic switches of said second module.

42. The device of claim 39, further comprising:

- (c) an uplink conduit;

and wherein each said module further includes, for each wavelength of the respective plurality:

- (iii) a mechanism for diverting, to said uplink conduit, the light of said each wavelength of said respective plurality remaining after said controllable portion of the light of said each wavelength of said respective plurality is switched to the output conduits.

43. A device for switching light of any of a plurality of discrete wavelengths from at least one of a plurality of input conduits to any one of a plurality of output conduits, comprising:

- (a) for each input conduit, a module including:
  - (i) for each wavelength and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength being optically coupled, and
  - (ii) for each wavelength, a mechanism for diverting the light of said each wavelength from said each input conduit to said respective electroholographic switches while passing the light of all other

wavelengths; and

- (b) for each output conduit, a multiplexer for combining outputs of all said respective electroholographic switches into said each output conduit.

44. A device for converting light of any of a first plurality of discrete wavelengths to light of any of a second plurality of discrete wavelengths, said first and second pluralities being equal in number, and then switching the light of the second plurality of discrete wavelengths to any of a plurality of output conduits, comprising:

- (a) a first module including:
  - (i) a plurality of transponders, equal in number to the first plurality of wavelengths, each said transponder outputting light of a respective wavelength of the second plurality, and
  - (ii) for each wavelength of the first plurality and for each transponder, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the first plurality to said each transponder, said electroholographic switches of a common transponder being optically coupled, said electroholographic switches of a common wavelength of the first plurality being optically coupled; and
- (b) a second module including:
  - (i) for each wavelength of the second plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the second plurality to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength of the second plurality being optically coupled.

45. The device of claim 44, wherein said first module further includes, for each wavelength of the first plurality:

- (iii) a mechanism for diverting the light of said each wavelength of the first plurality to said respective electroholographic switches while passing the light of all other wavelengths.

46. The device of claim 44, wherein said first module further includes:

- (iii) for each of at least a portion of the wavelengths of the first plurality, a detector for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the transponders.

47. The device of claim 46, wherein said second module further includes:

- (ii) for each of at least a portion of the wavelengths of the second plurality, a detector for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits.

48. In an optical communication system wherein signals are carried in a plurality of channels, each channel including light of a respective discrete wavelength, an add-drop multiplexer, for replacing at least one input signal with a corresponding at least one output signal on a respective subplurality of the channels, comprising:

- (a) an uplink conduit;
- (b) a drop module including:
  - (i) a plurality of diversion conduits,
  - (ii) for each wavelength of the subplurality and for each said diversion conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the subplurality to said each diversion conduit, said electroholographic switches of a common diversion conduit being optically coupled, said electroholographic switches of a common wavelength of the subplurality being optically coupled, and

- (iii) a mechanism for diverting the light of said each wavelength of said subplurality to said respective electroholographic switches while passing the light of all other wavelengths to said uplink conduit; and
- (c) an add module including:
  - (i) a plurality of substitution conduits, and
  - (ii) a mechanism for diverting light of the wavelengths of the subplurality from each said substitution conduit to said uplink conduit.

49. The add-drop multiplexer of claim 48, wherein said mechanism for diverting light of the wavelengths of the subplurality from each said substitution conduit to said uplink includes one y-junction for each said substitution conduit.

50. The add-drop multiplexer of claim 48, wherein said mechanism for diverting light of the wavelengths of the subplurality from each said substitution conduit to said uplink includes one wide-band switch for each said substitution conduit.

51. The add-drop multiplexer of claim 48, wherein said mechanism for diverting light of the wavelengths of the subplurality from each said substitution conduit to said uplink includes one electroholographic switch for each said substitution conduit.

52. In an optical communications system wherein signals are carried in a plurality of channels via a common conduit, each channel having a respective discrete wavelength, a device for tapping the channels, comprising:

- (a) for each channel, a respective electroholographic switch for diverting a controllable portion of said signals of said each channel from the common conduit.

53. The device of claim 52, further comprising:
- (b) for each channel, a mechanism for measuring an intensity of said controllable portion of said signals of said each channel.

54. The device of claim 53, further comprising:
- (c) an amplifier, upstream from said electroholographic switches, for amplifying the intensities of the channels; and
  - (d) a mechanism, upstream of said amplifier, for adjusting the intensities of the channels, based on said measured intensities of said controllable portions of said signals.

55. An electroholographic switch, for switching light of a certain wavelength, comprising:

- (a) a crystal of a photorefractive material including a plurality of electroholographic gratings, said electroholographic gratings being spaced apart laterally within said crystal; and
- (b) for each said electroholographic grating, two electrodes for activating said each grating.

56. The device of claim 55, wherein said photorefractive material is selected from the group consisting of potassium tantalate niobate, strontium barium niobate and potassium lithium tantalate niobate.

57. An optical switch comprising a paraelectric photorefractive material, wherein is stored a plurality of superposed holograms whose reconstruction is controllable by means of an applied electric field.

58. A method for determining a level of amplification of an optical signal for switching the optical signal to a primary output conduit, the method comprising the steps of:

- (a) providing at least one electroholographic switch for switching the optical signal to the primary output conduit;

- (b) diverting a first portion of the optical signal through said electroholographic switch to the primary output conduit and a second portion of the optical signal through said electroholographic switch to a secondary output conduit;
- (c) detecting a power of said second portion; and
- (d) based on said detected power of said second portion, adjusting a power of said first portion.

59. The method of claim 58, wherein said adjusting of said power of said first portion is effected by applying a corresponding voltage to each of said at least one electroholographic switch.

60. The method of claim 58, wherein the optical signal comprises a plurality of wavelengths, each of said plurality of wavelengths being switched by a respective electroholographic switch to a respective primary output conduit.

61. A method for analyzing at least one quality characteristic of an optical signal, the method comprising the steps of:

- (a) providing an electroholographic switch for diverting at least a portion of the optical signal for analysis;
- (b) diverting said at least a portion of the optical signal for analysis; and
- (c) analyzing said at least a portion of the optical signal to determine the at least one quality characteristic.

62. The method of claim 61, wherein said at least one quality characteristic is a saturation of a level of the optical signal to said electroholographic switch, wherein step (c) further comprises the steps of:

- (i) converting said at least a portion of the optical signal to a voltage;
- (ii) comparing said voltage to a maximum preset high threshold; and
- (iii) if said voltage is greater than said maximum preset high threshold, determining that said level of the optical signal to said

electroholographic switch is saturated.

63. The method of claim 61, wherein said at least one quality characteristic is a low level of the optical signal to said electroholographic switch, wherein step (c) further comprises the steps of:

- (i) converting said at least a portion of the optical signal to a voltage;
- (ii) comparing said voltage to a minimum preset low threshold; and
- (iii) if said voltage is less than said minimum preset low threshold, determining that said level of the optical signal to said electroholographic switch is at said low level.

64. The method of claim 61, wherein said at least one quality characteristic is a power of the optical signal to said electroholographic switch, wherein step (c) further comprises the steps of:

- (i) converting said at least a portion of the optical signal to a voltage;
- (ii) converting said voltage to a digital signal; and
- (iii) determining said power of the optical signal from said digital signal.

65. The method of claim 61, wherein said at least one quality characteristic is an attenuation of the optical signal.

66. The method of claim 61, wherein the optical signal comprises a plurality of wavelengths, and step (a) further comprises the step of providing a plurality of electroholographic switches, each of said plurality of electroholographic switches being dedicated to one of said plurality of wavelengths, such that steps (b) and (c) are performed for each of said plurality of wavelengths.

67. The method of claim 66, wherein steps (b) and (c) are performed sequentially for each of said plurality of wavelengths.

68. The method of claim 66, wherein steps (b) and (c) are performed

substantially simultaneously for at least two of said plurality of wavelengths.

69. A method of communication wherein optical signals are transmitted through an optical communication network, the optical signals being encoded in a plurality of channels propagating in an optical medium, the method comprising the steps of:

- (a) diverting only a portion of the optical signals in each channel while a remainder of the optical signals in each channel continues to propagate in the optical medium;
- (b) converting each portion to an electronic signal; and
- (c) managing the network in accordance with said electronic signal.



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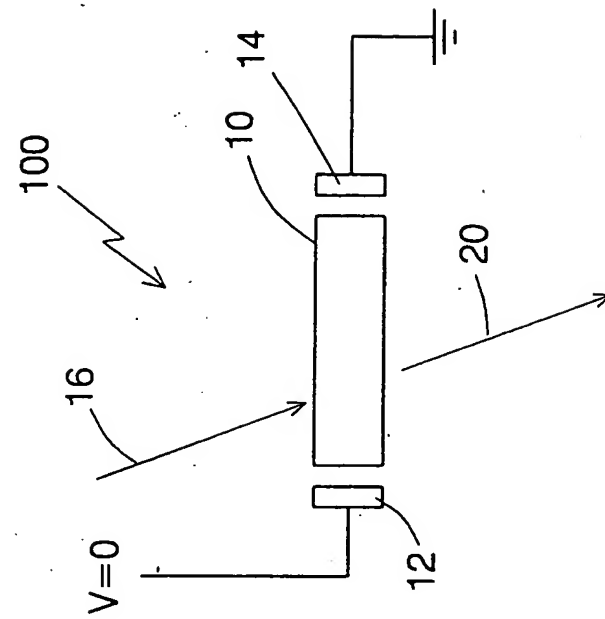


FIG. 1B  
(PRIOR ART)

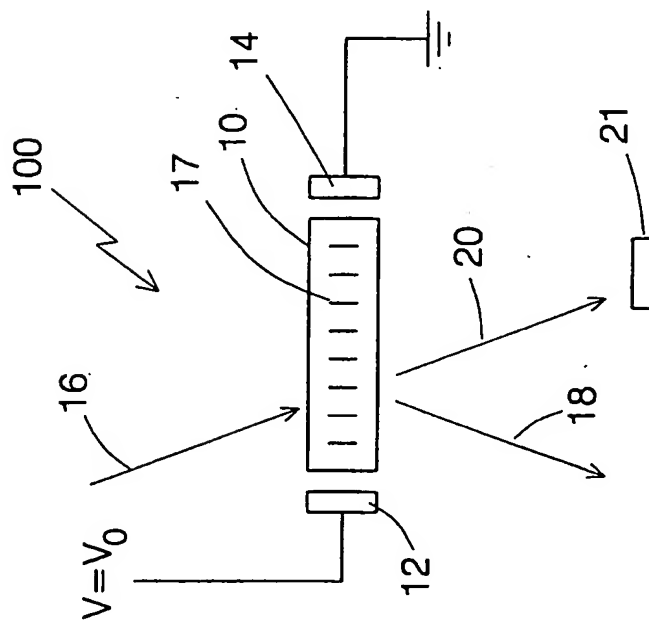


FIG. 1A  
(PRIOR ART)

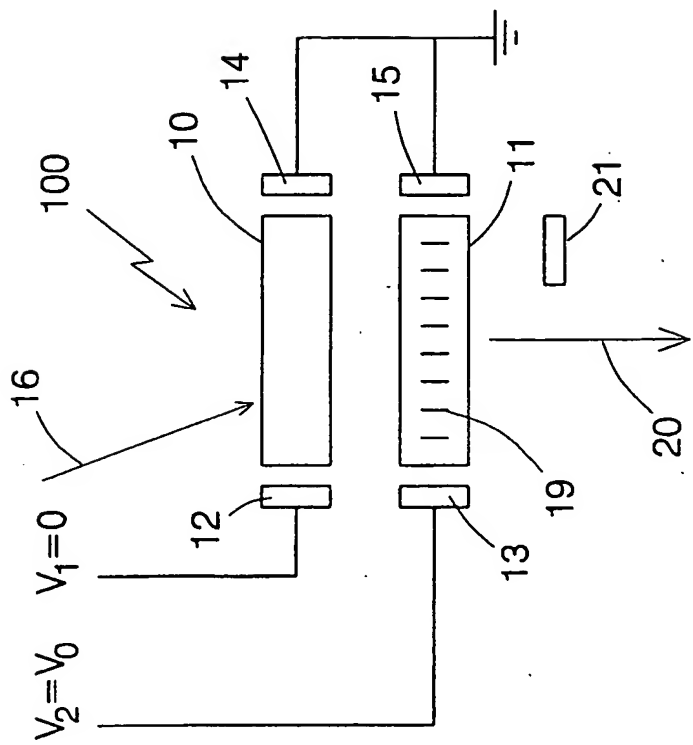


FIG. 1D  
(PRIOR ART)

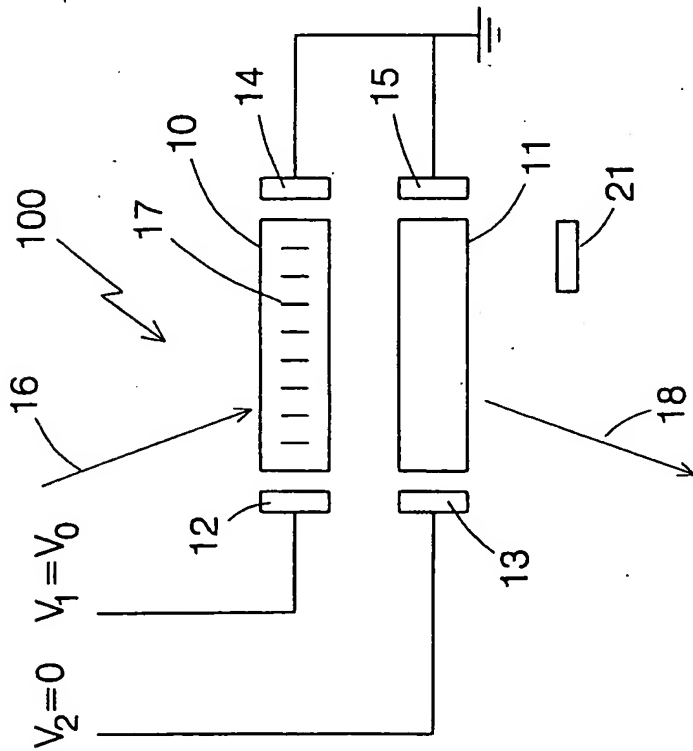


FIG. 1C  
(PRIOR ART)

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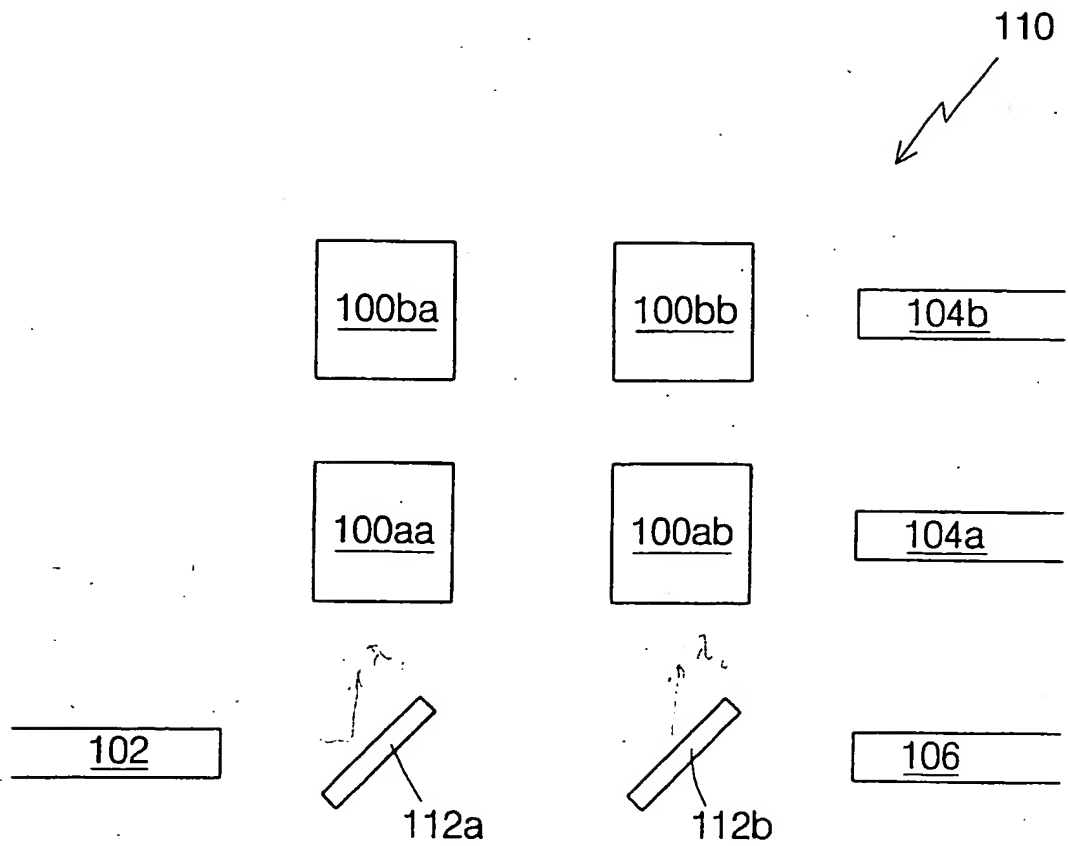


FIG. 2

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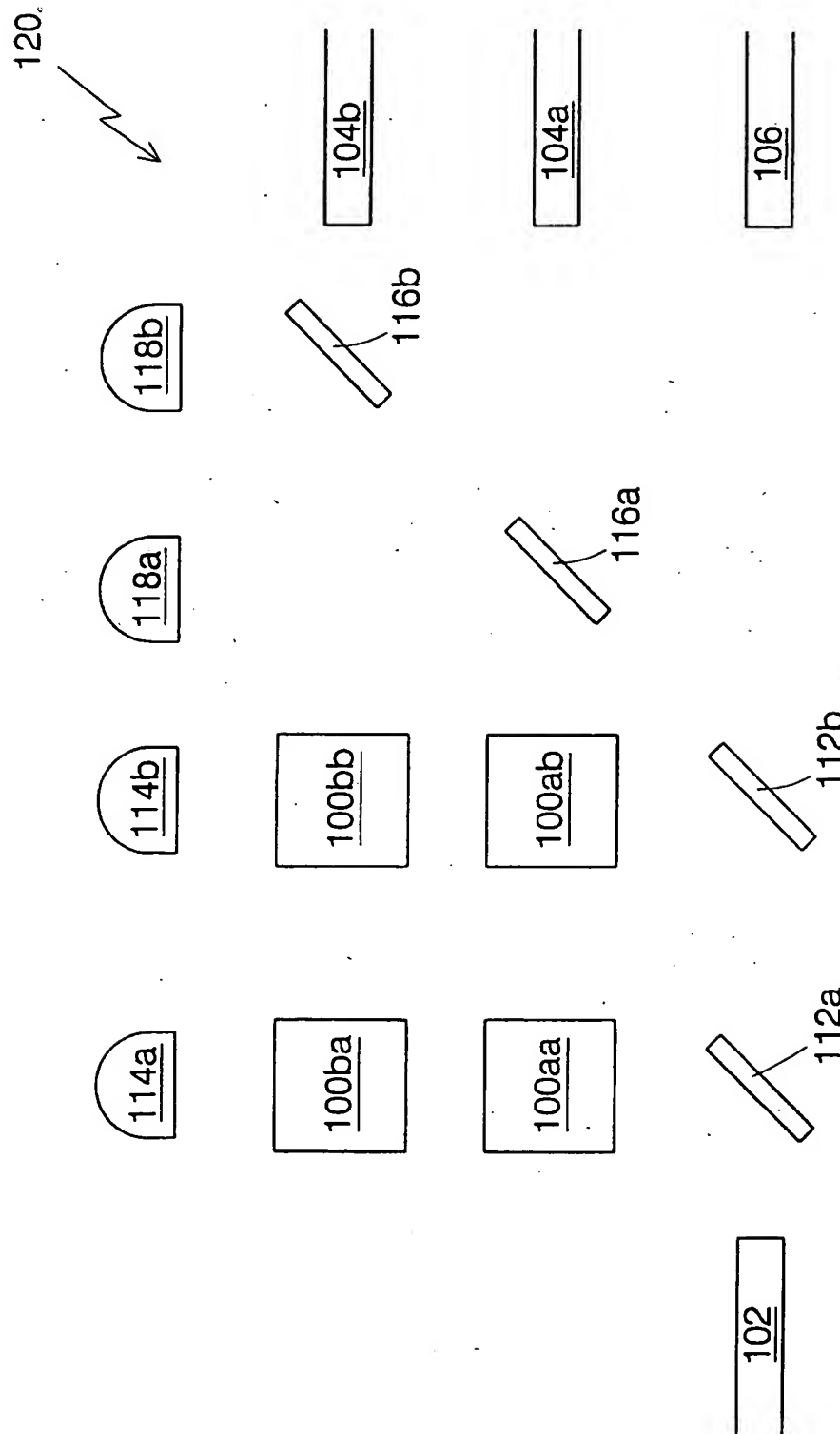


FIG. 3

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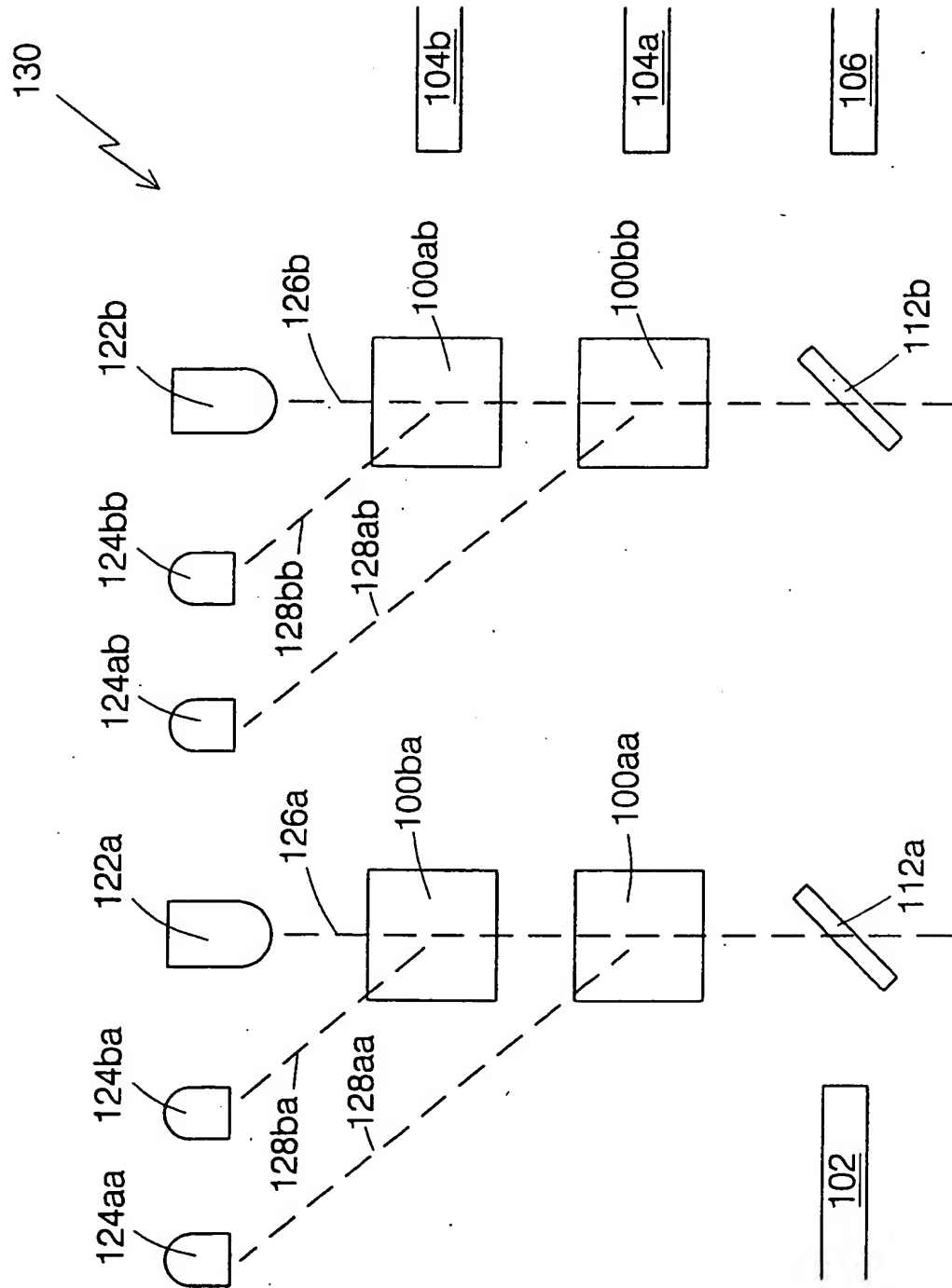


FIG. 4

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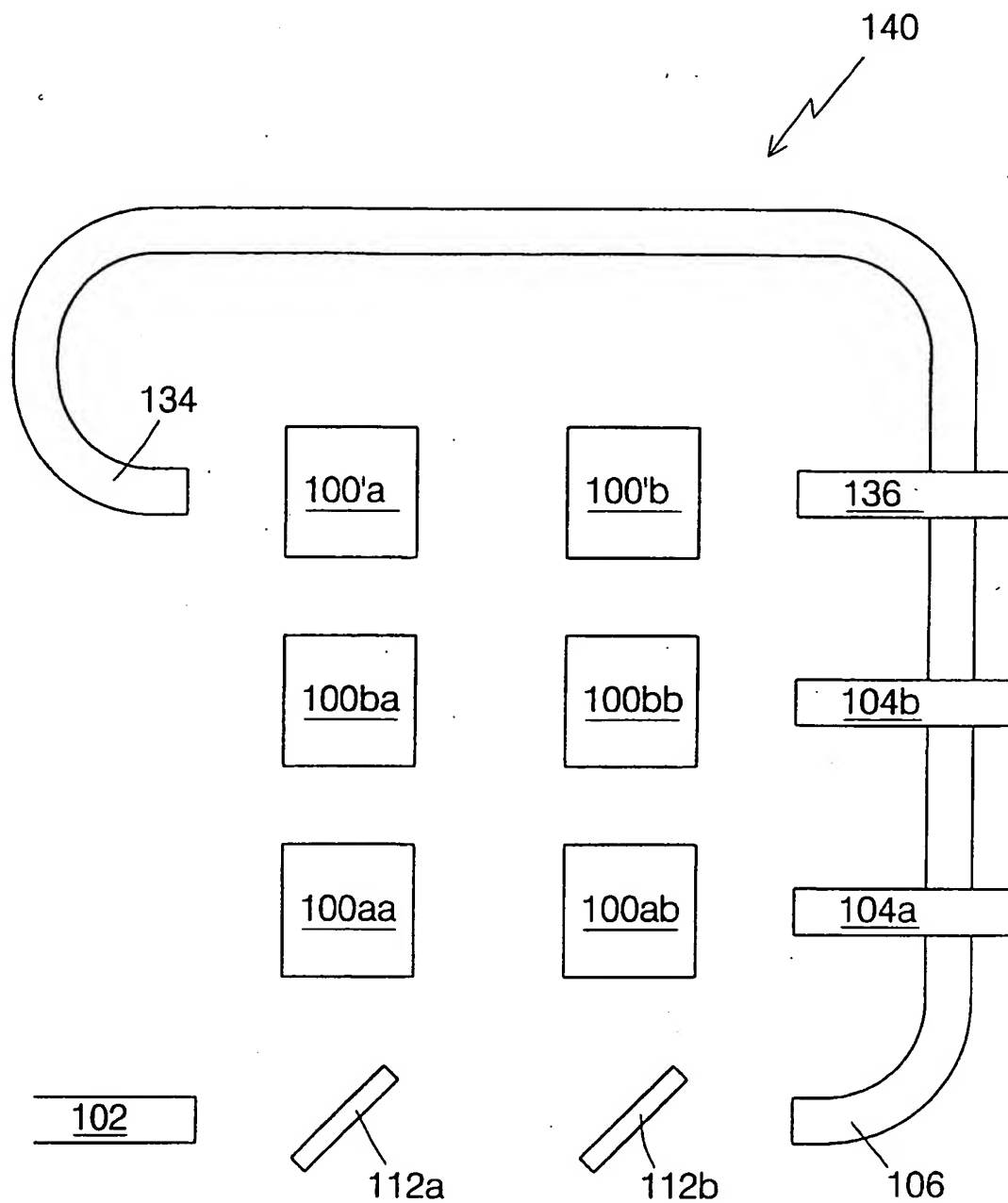


FIG. 5

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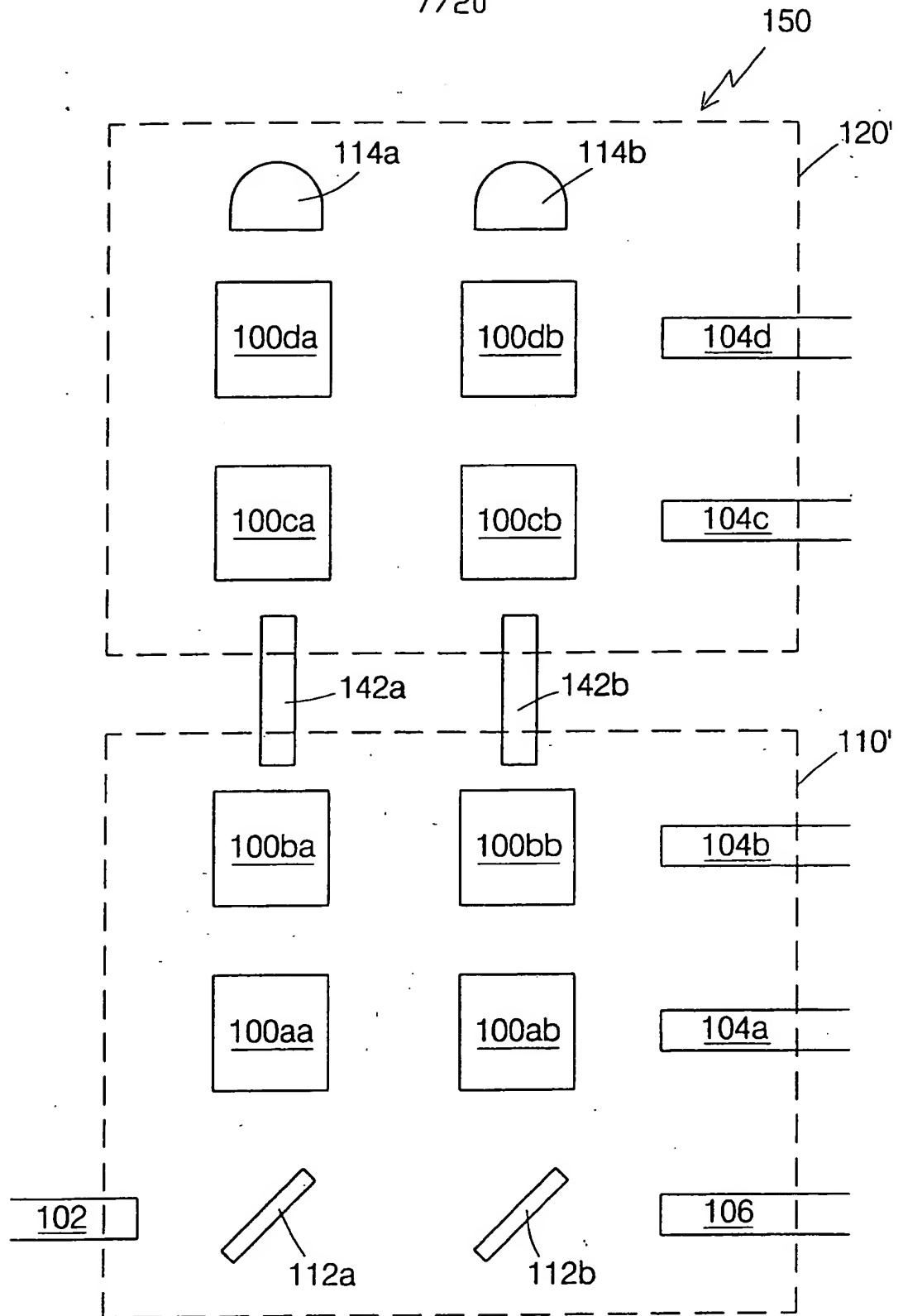


FIG. 6

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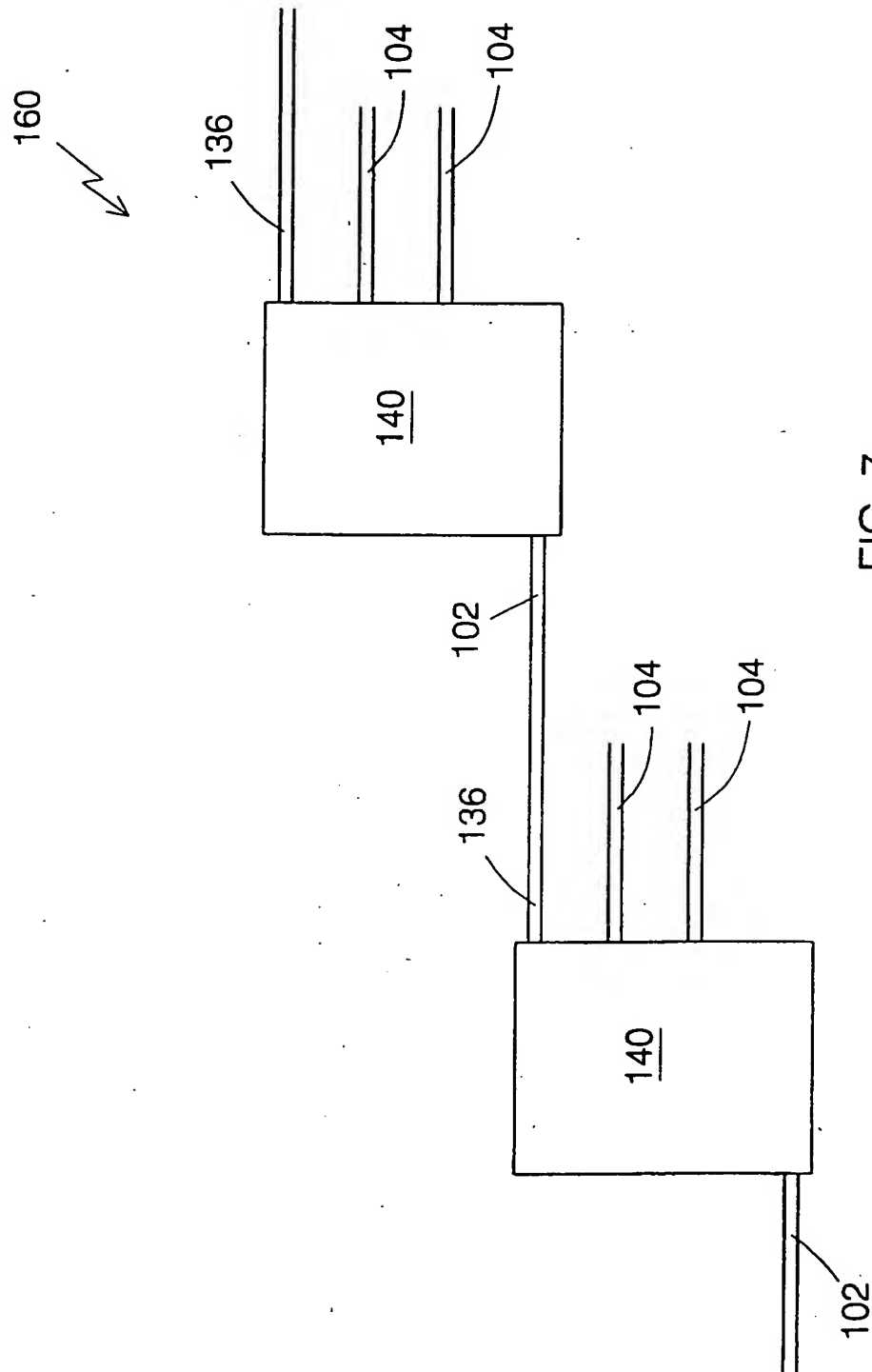
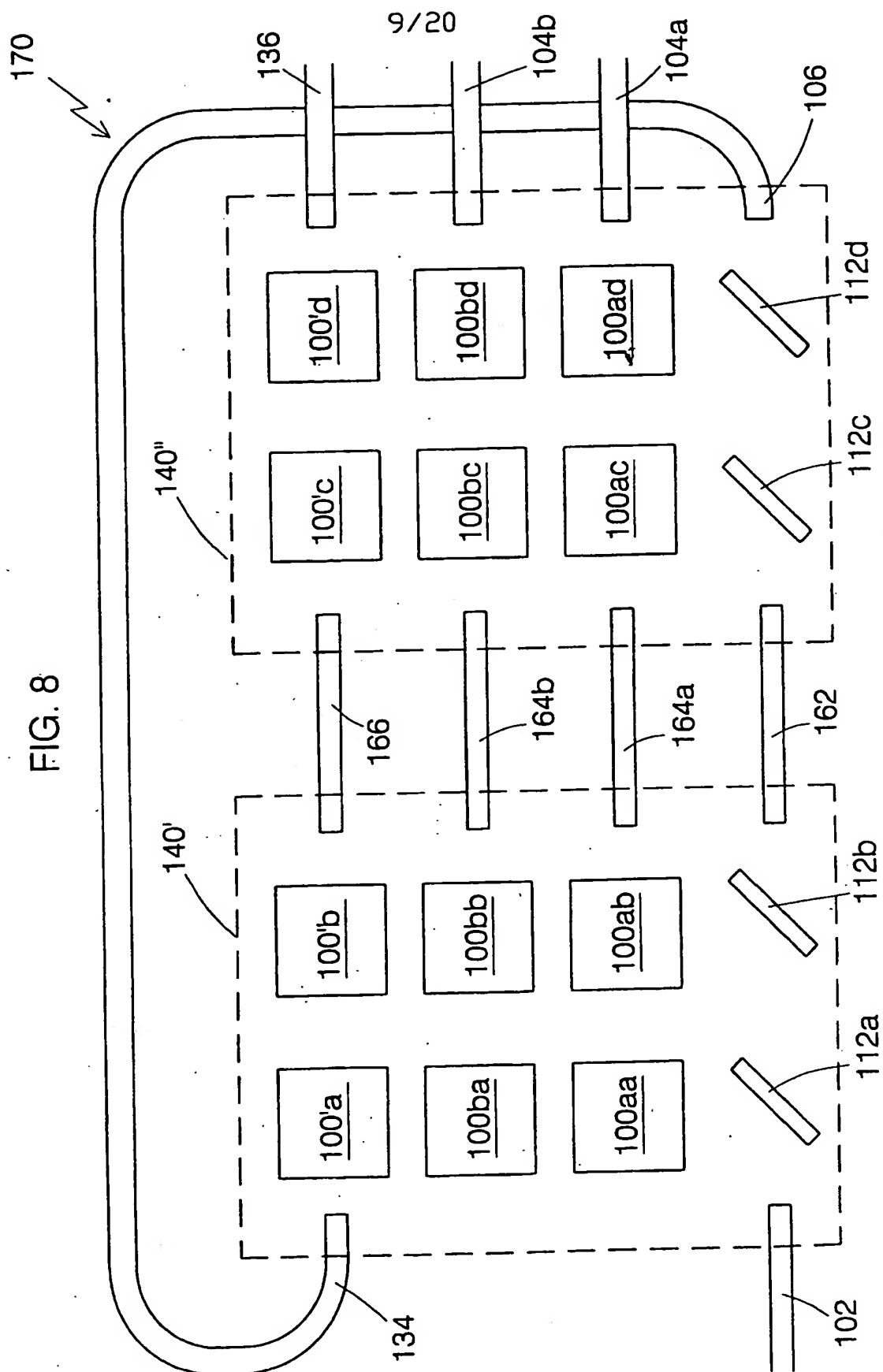


FIG. 7



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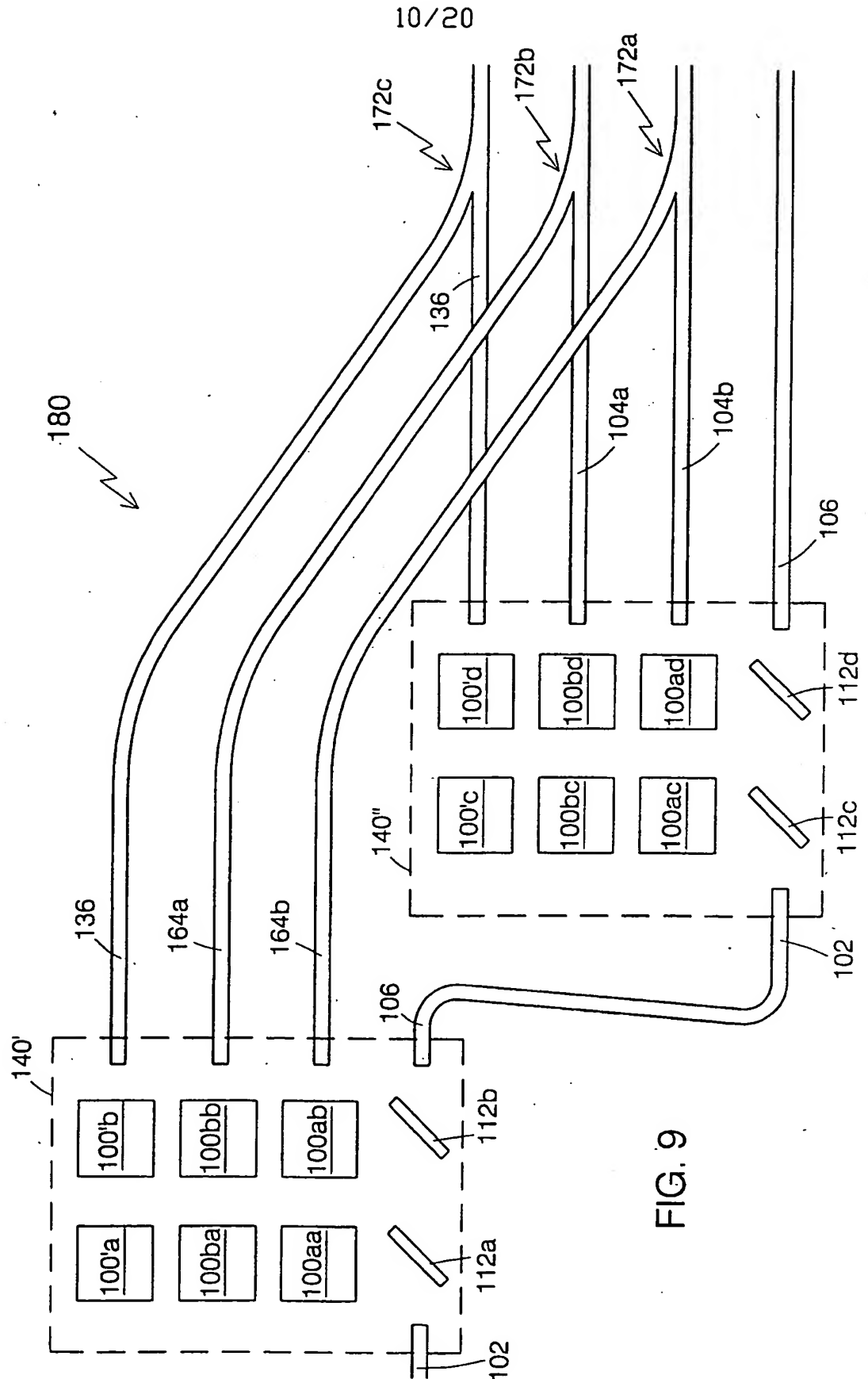
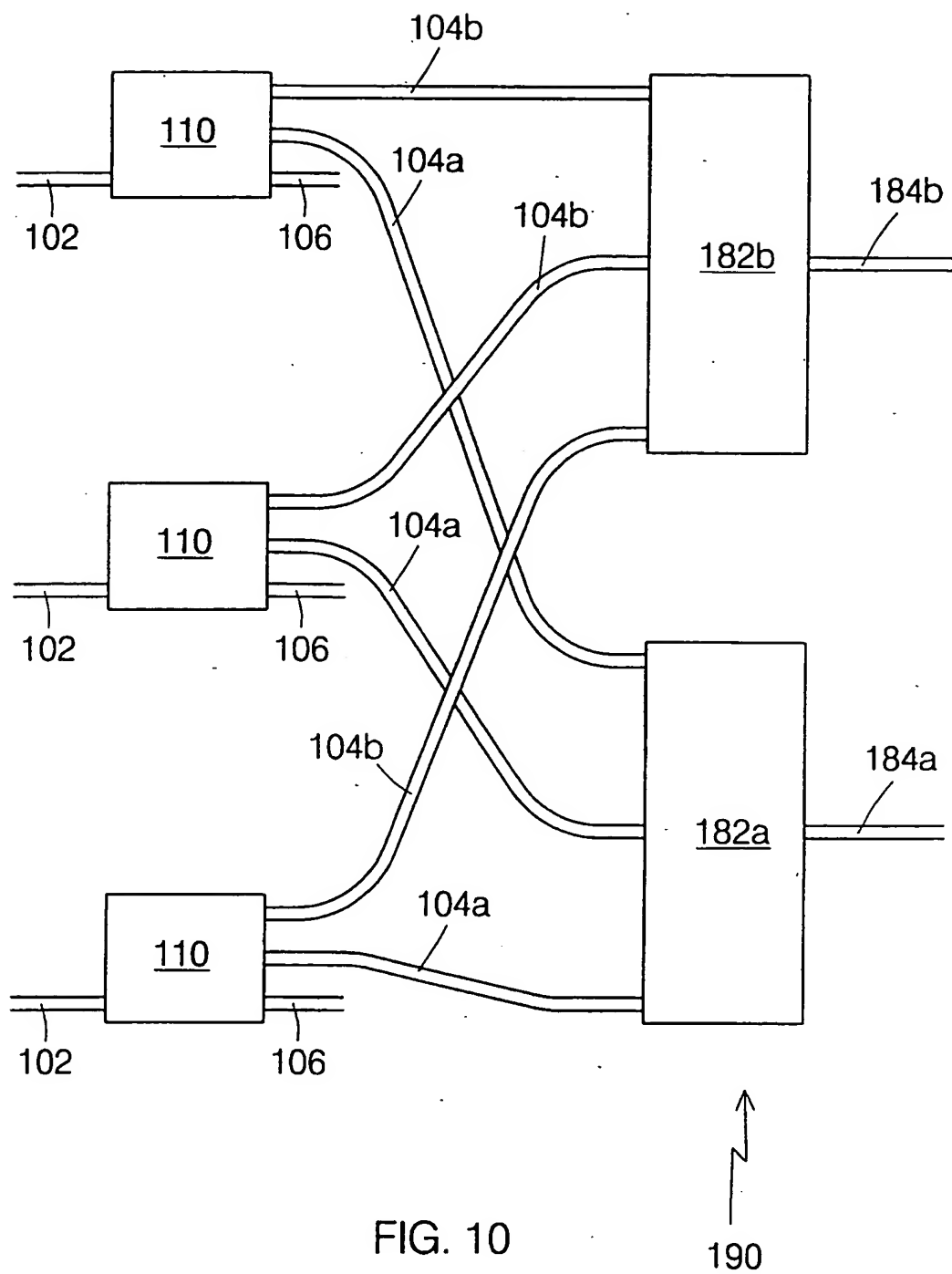


FIG. 9

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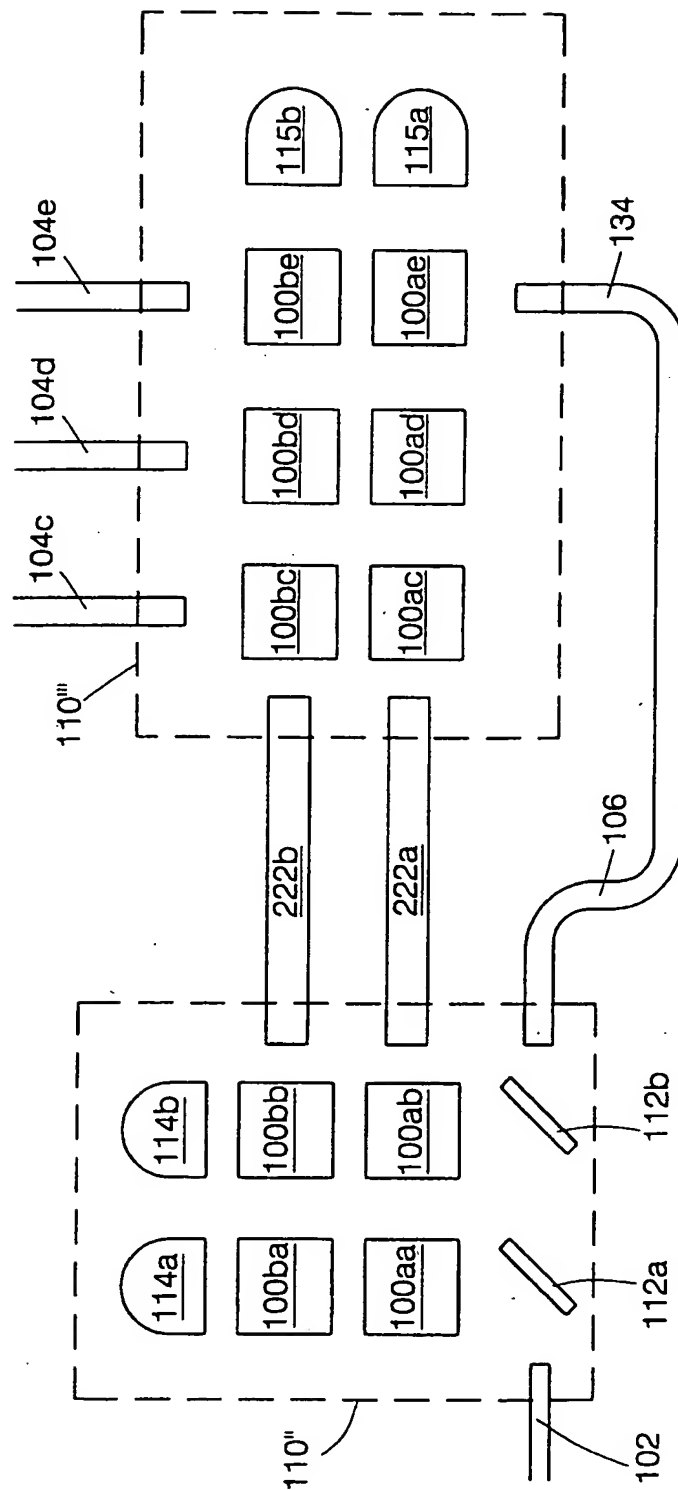


FIG. 11

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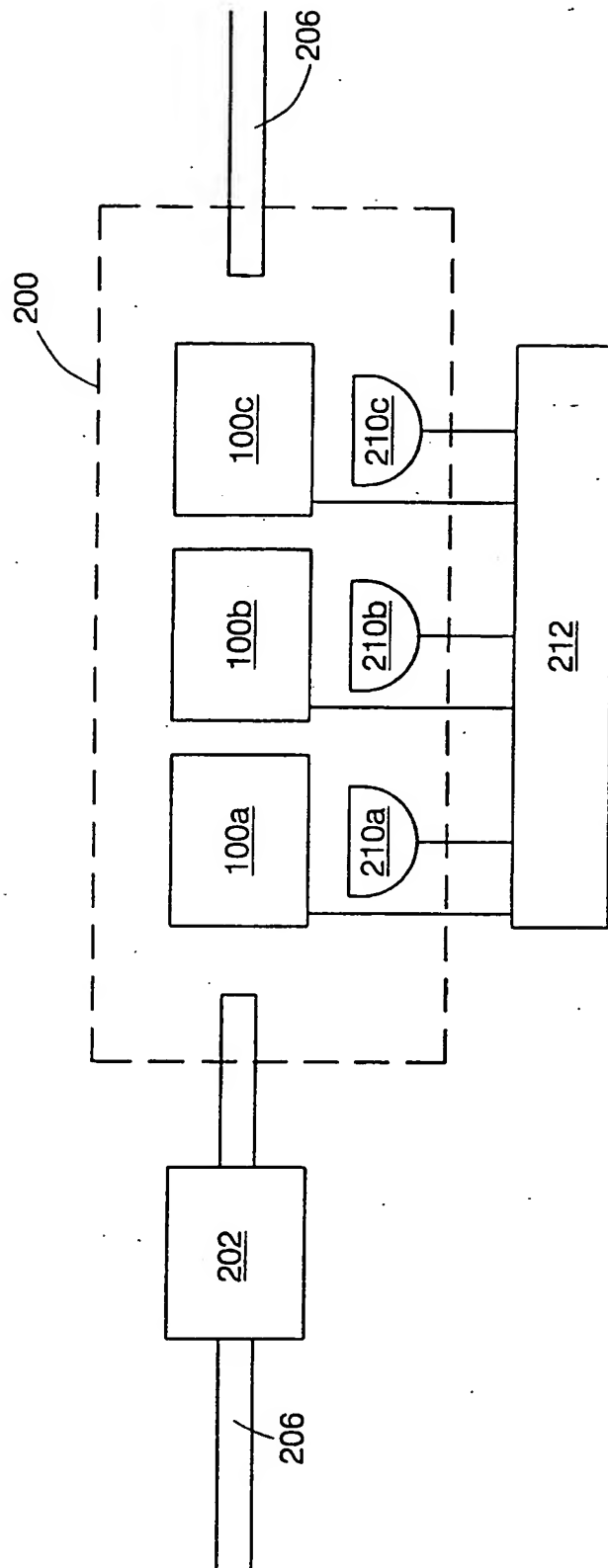


FIG. 12

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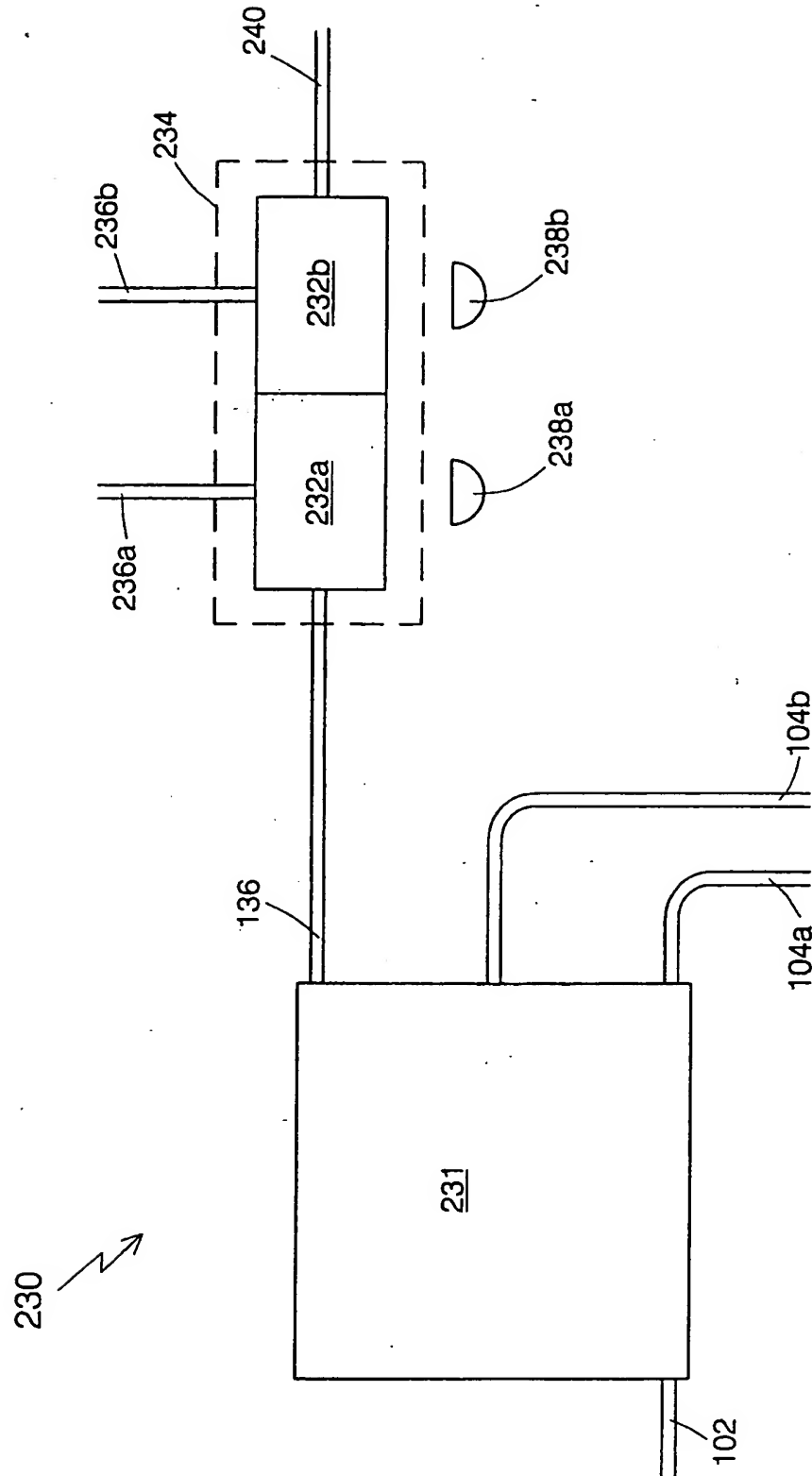


FIG. 13

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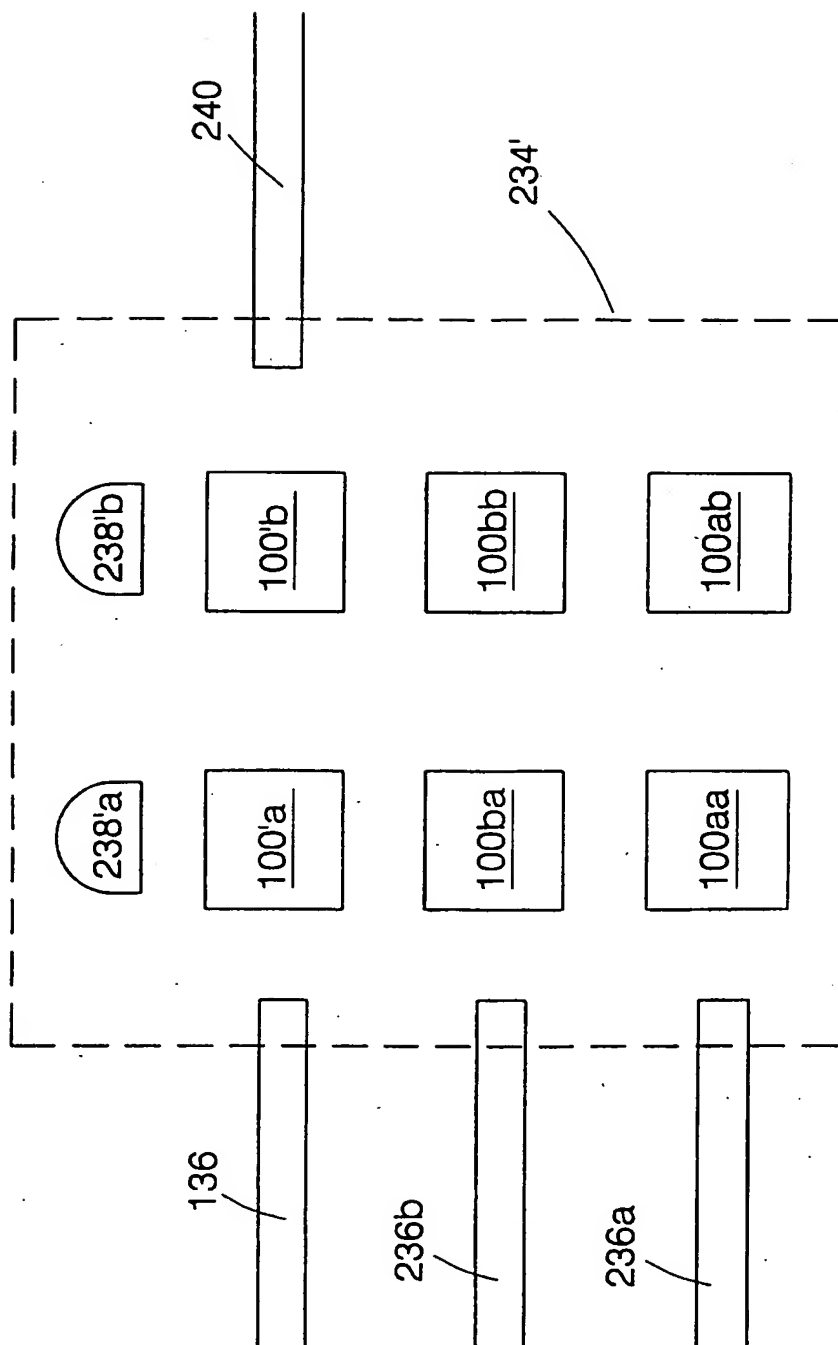


FIG. 14

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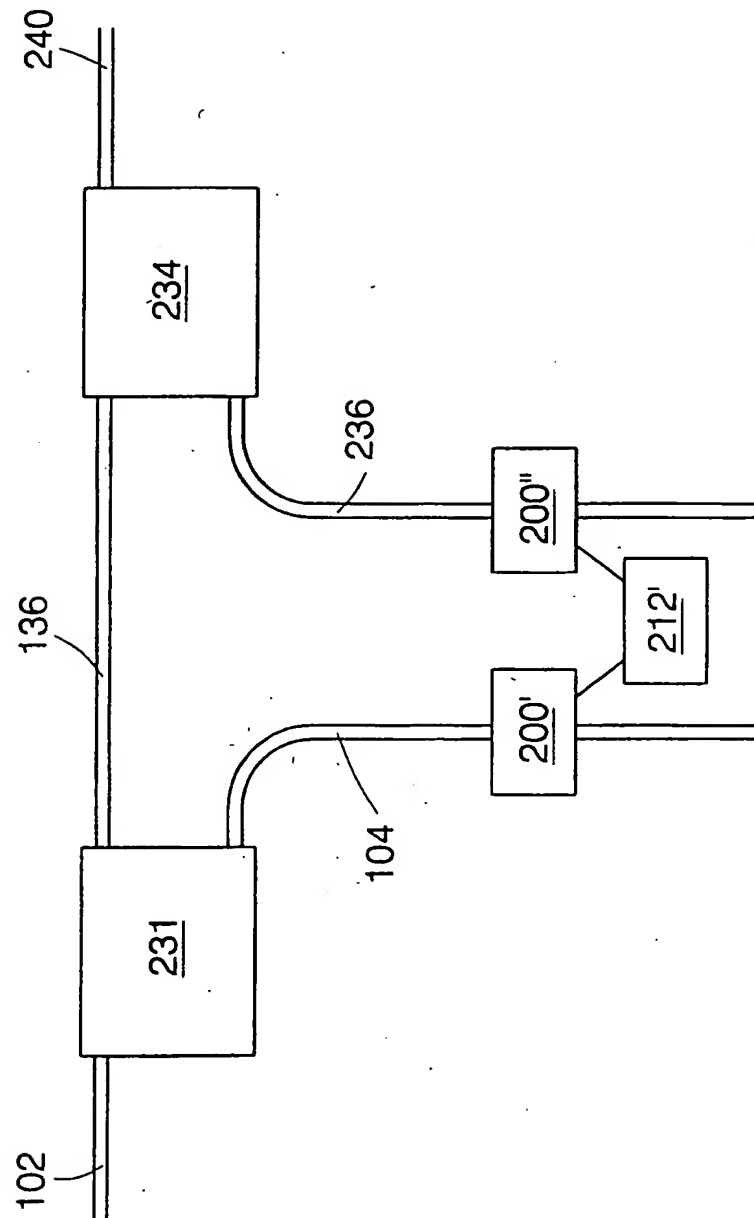


FIG. 15



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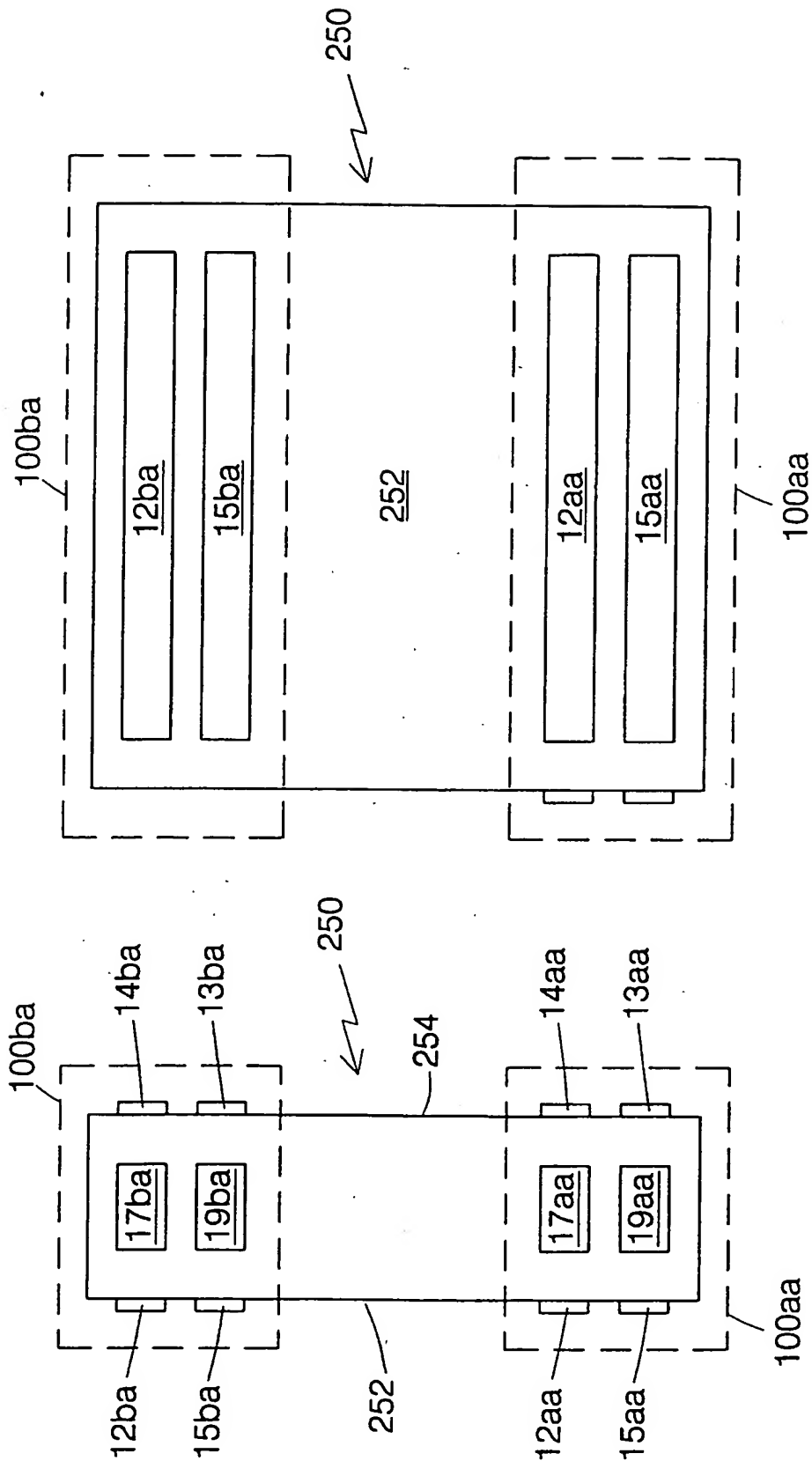


FIG. 16B

FIG. 16A

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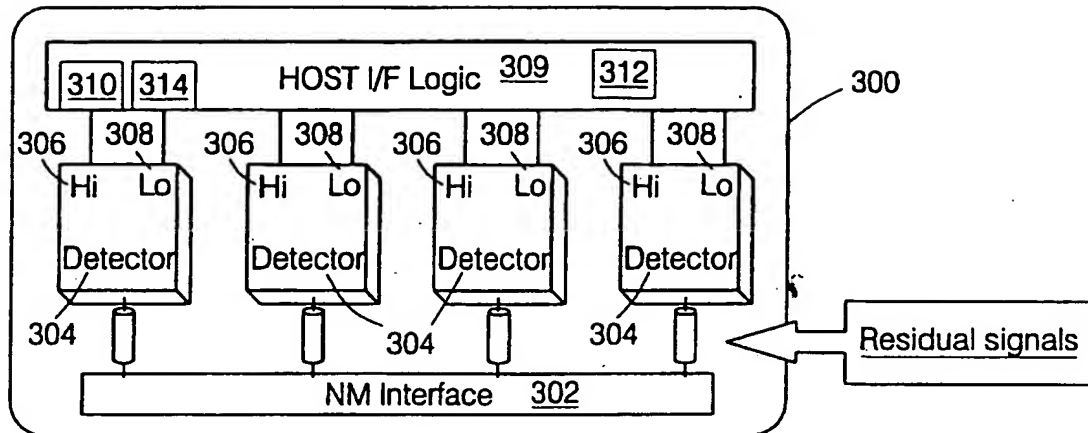


FIG. 17

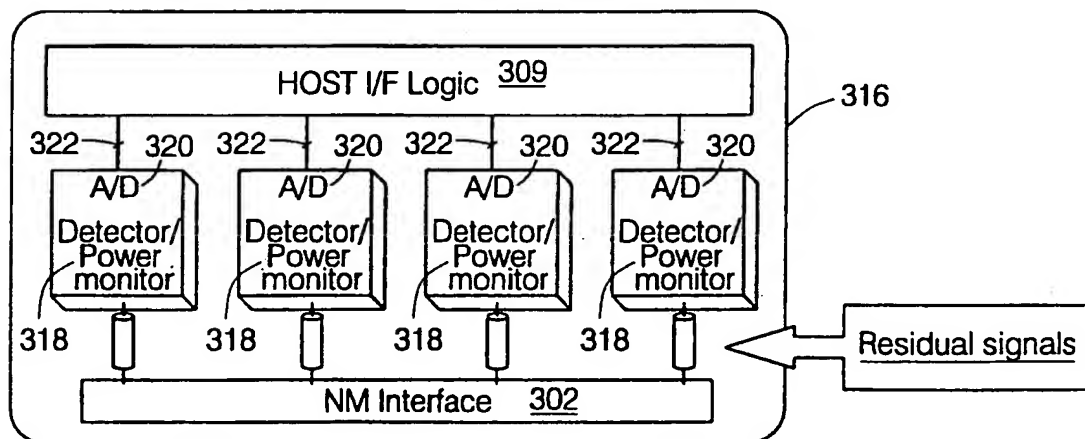


FIG. 18

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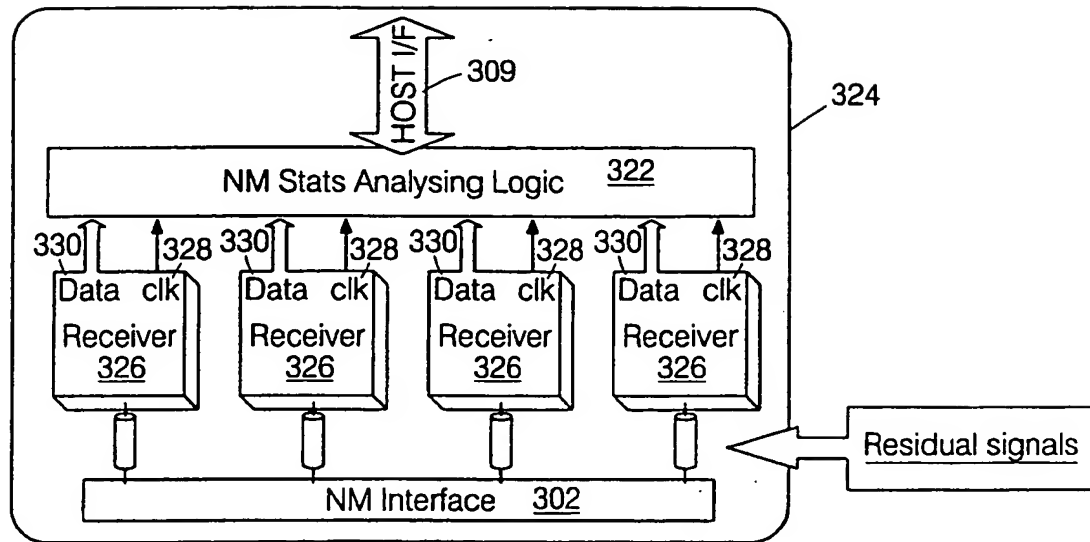


FIG. 19

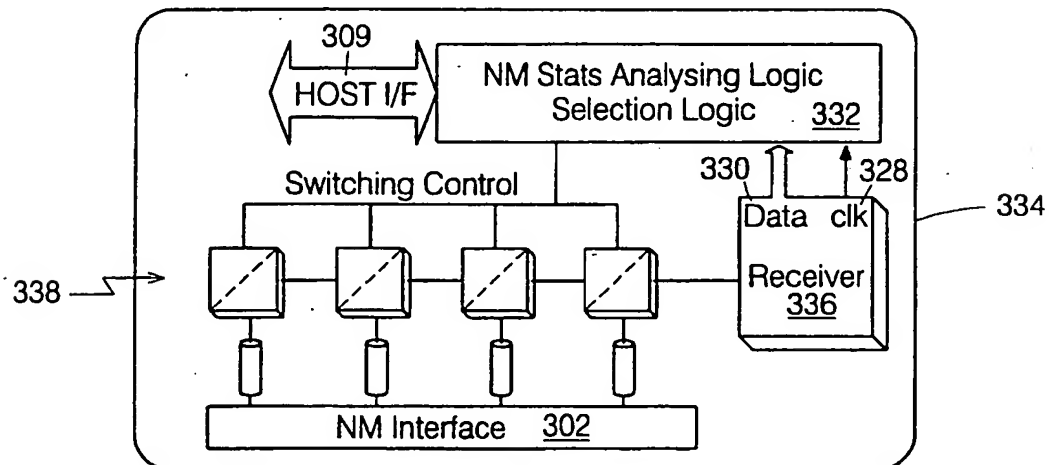


FIG. 20

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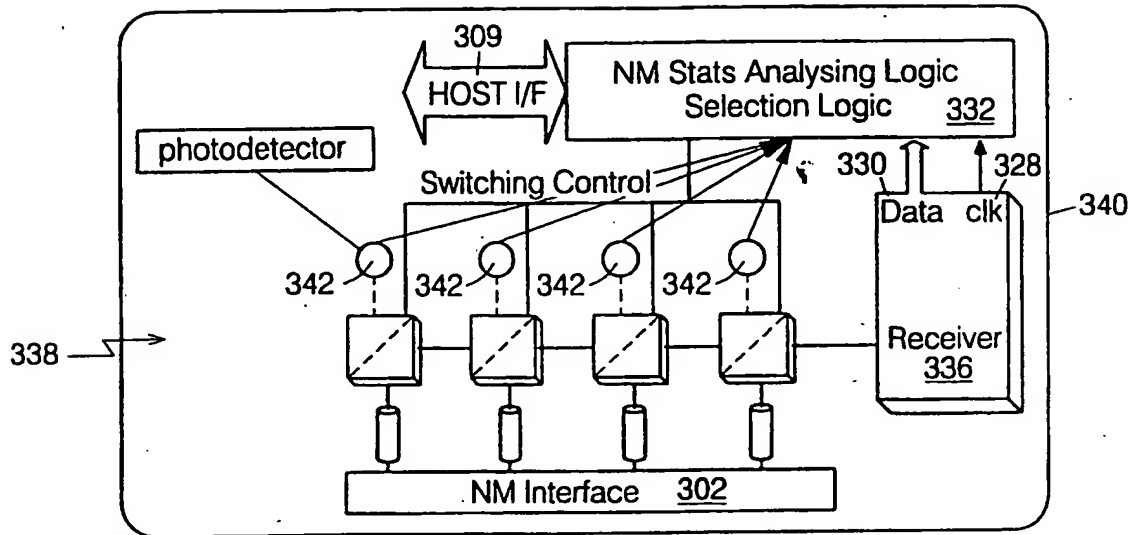


FIG. 21

## INTERNATIONAL SEARCH REPORT

 International application No.  
PCT/IL00/00426

<b>A. CLASSIFICATION OF SUBJECT MATTER</b> IPC(7) : G02B 6/28; H04J 14/02 US CL : 385/24, 37, 41; 359/152, 163 According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b> Minimum documentation searched (classification system followed by classification symbols) U.S. : 385/24, 37, 41; 359/152, 163 Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched NONE Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) NONE		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US 6,108,471 A (ZHANG et al.) 22 August 2000 (22/08/00) entire document.	1-69
Y	US 5,825,949 A (CHOY et al.) 20 October 1998 (21/10/98), entire document.	1-69
Y	US 5,121,231 A (JENKINS et al.) 09 June 1992 (09/06/92) entire document	1-69
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input type="checkbox"/> See patent family annex.		
* Special categories of cited documents: *A* document defining the general state of the art which is not considered to be of particular relevance *E* earlier document published on or after the international filing date *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) *O* document referring to an oral disclosure, use, exhibition or other means *P* document published prior to the international filing date but later than the priority date claimed	*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art *A* document member of the same patent family	
Date of the actual completion of the international search 15 DECEMBER 2000		Date of mailing of the international search report 08 JAN 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230		Authorized officer M. GELLNER <i>M. Gellner</i> Telephone No. (703) 305-3303